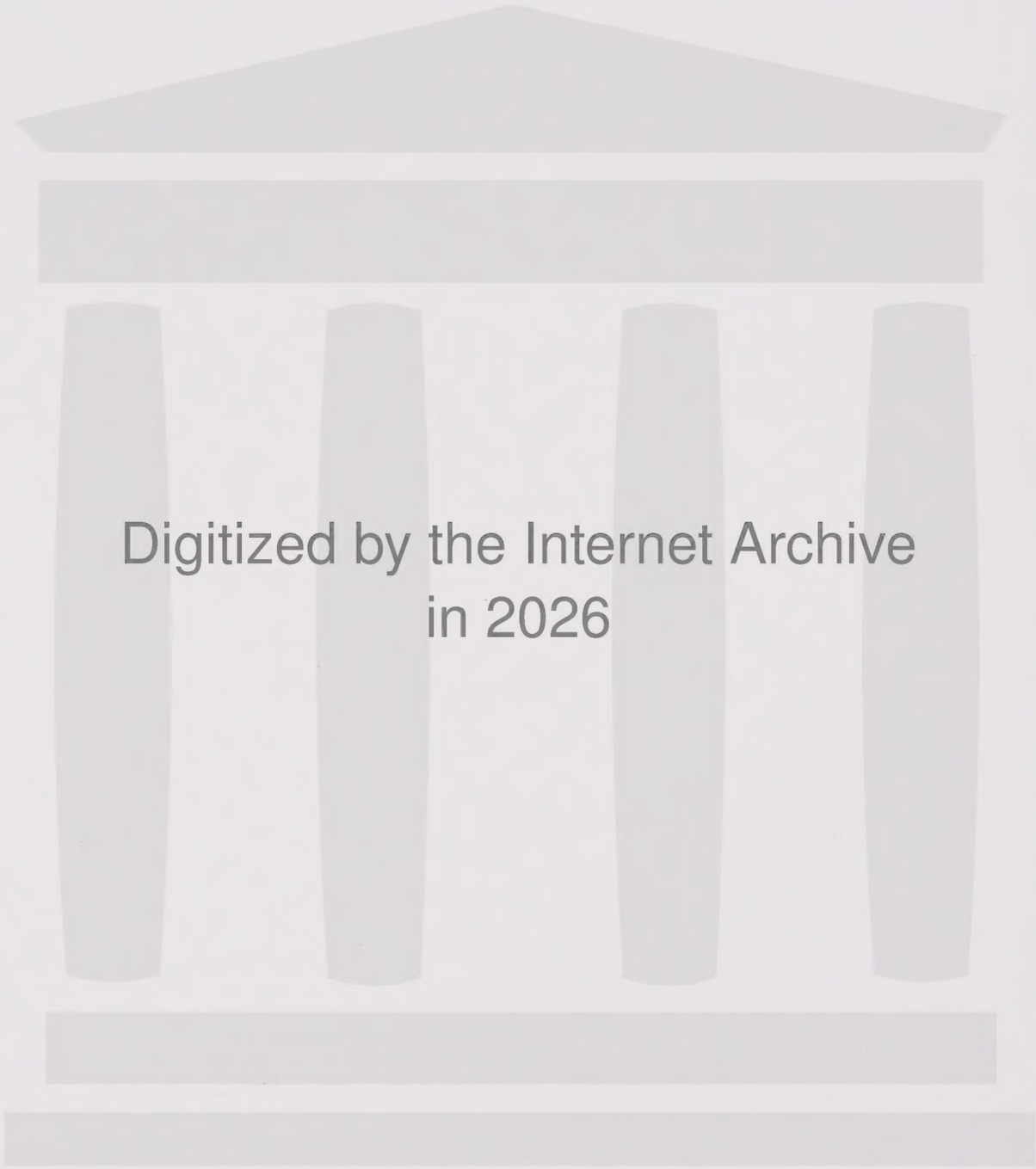
THE SCENE MACHINE

Theodor Holm Nelson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THE SCENE MACHINE

THE FANTASM™ SURFACE SIMULATION ARRAY

Hardware and methods
for
photorealistic animation graphics (CGI),
1971

Theodor Holm Nelson

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Mindful Press, 3020 Bridgeway #295, Sausalito CA 94965

THE SCENE MACHINE

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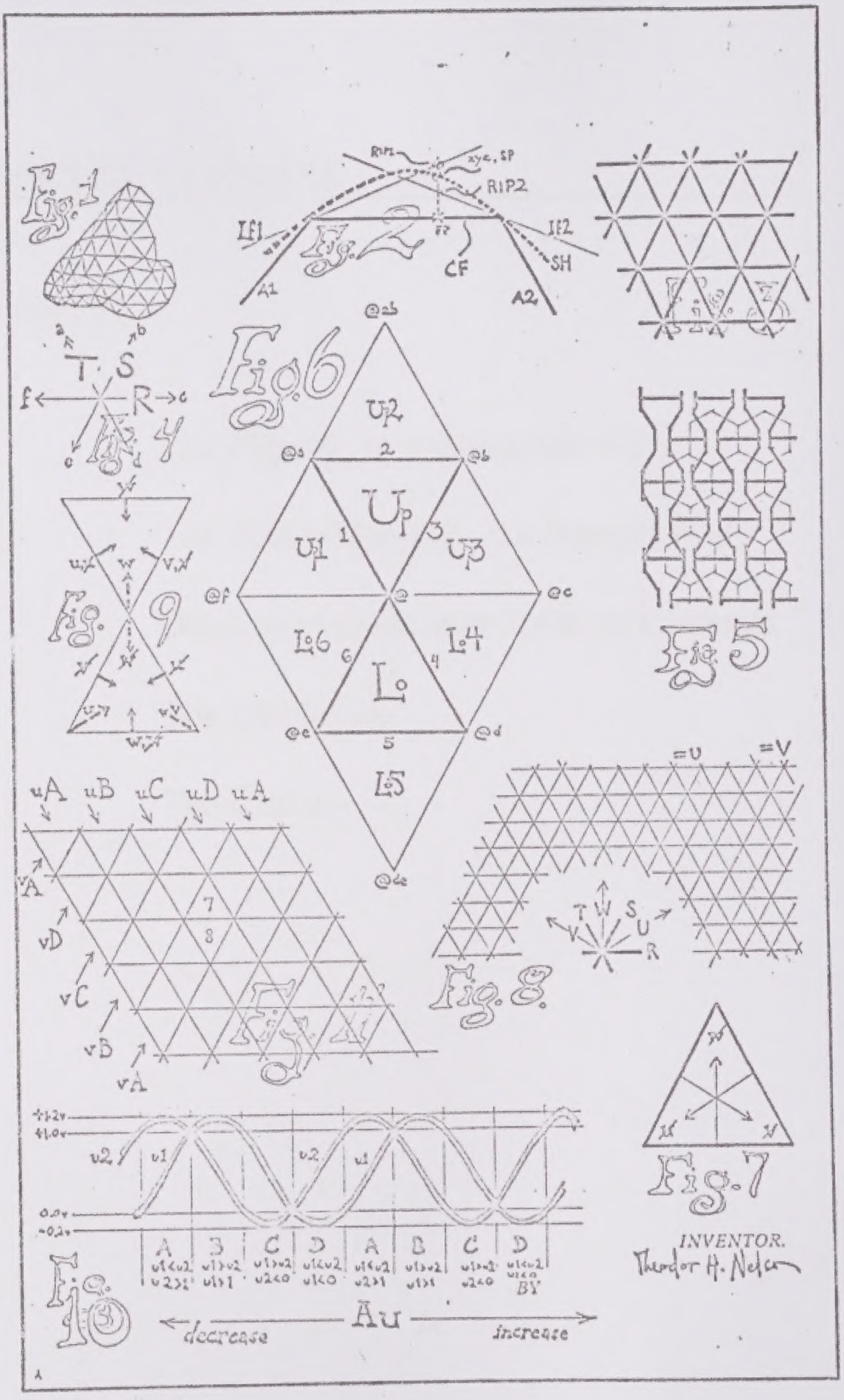
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Theodor H. Nelson

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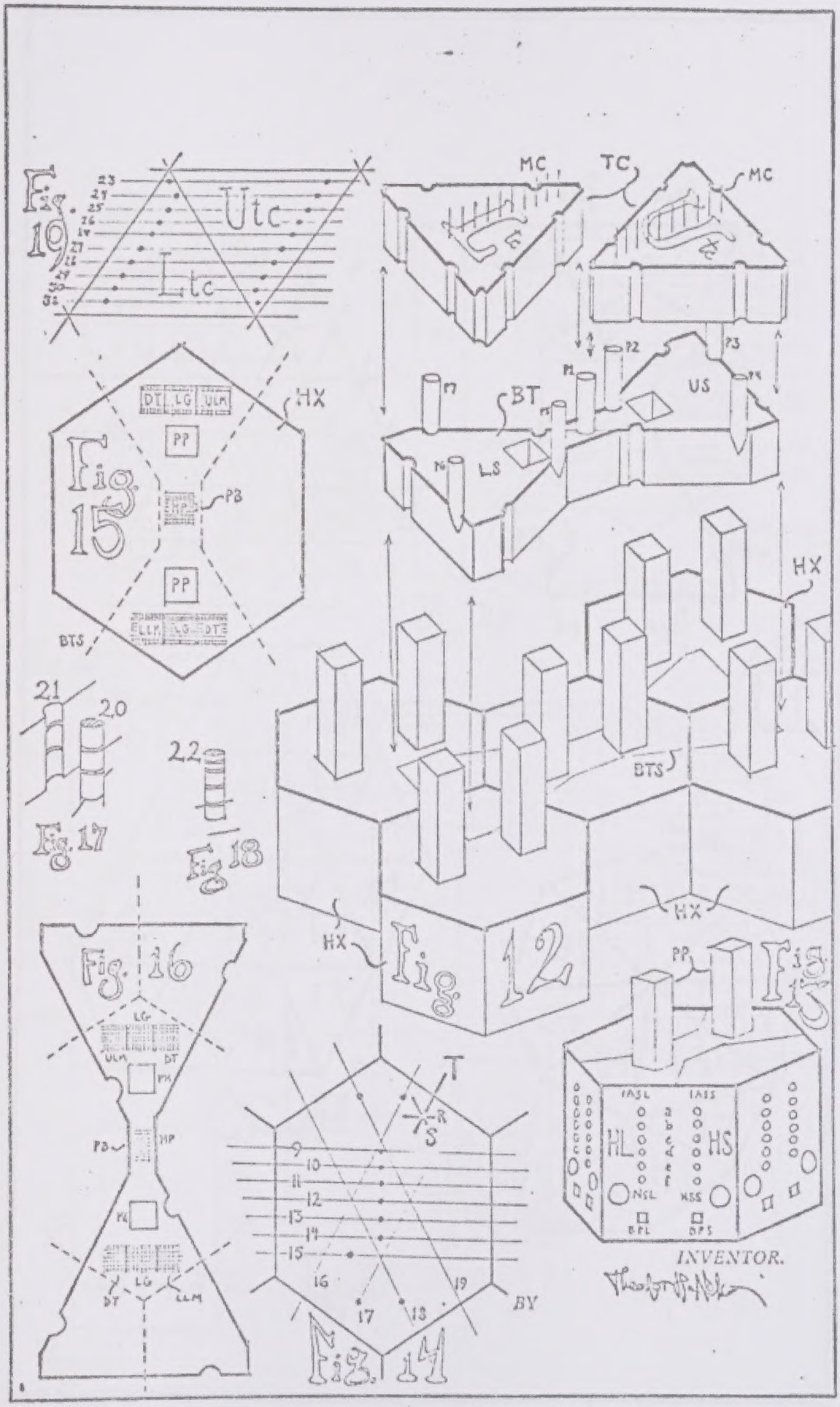
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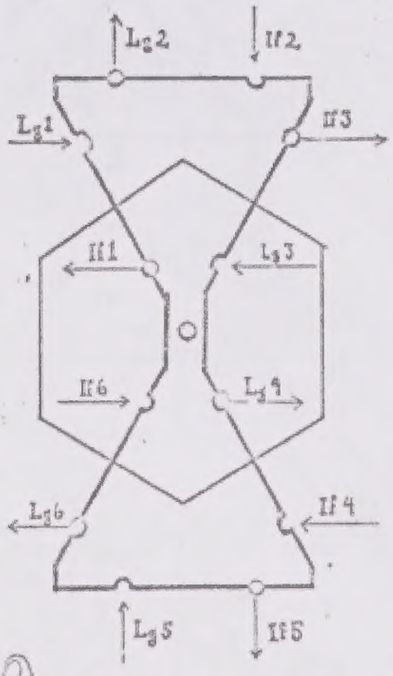

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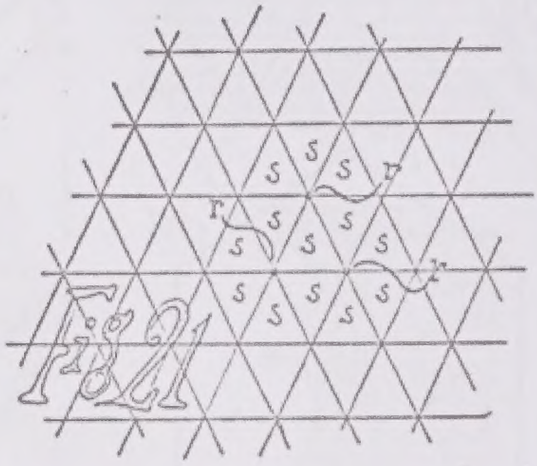

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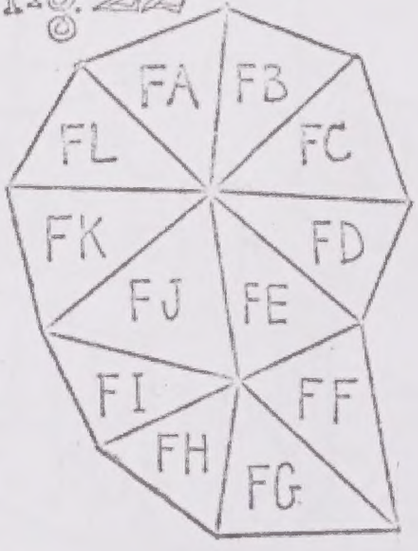

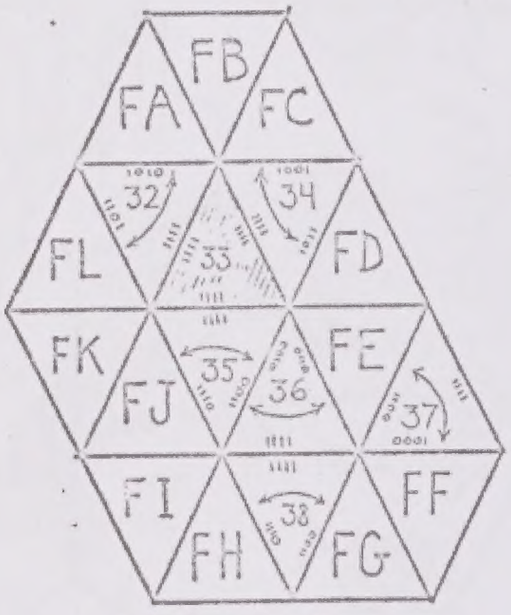

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INVENTOR.
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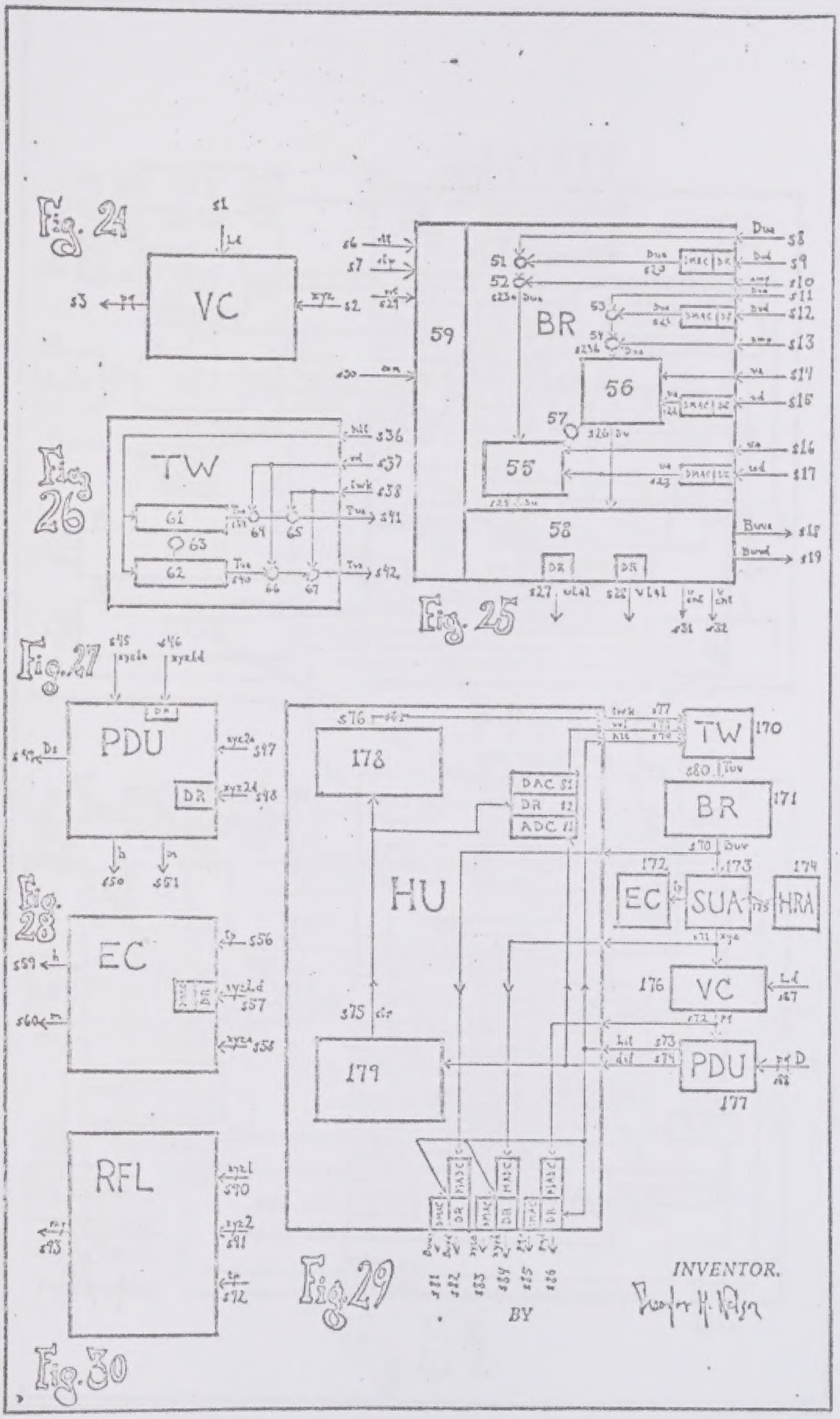
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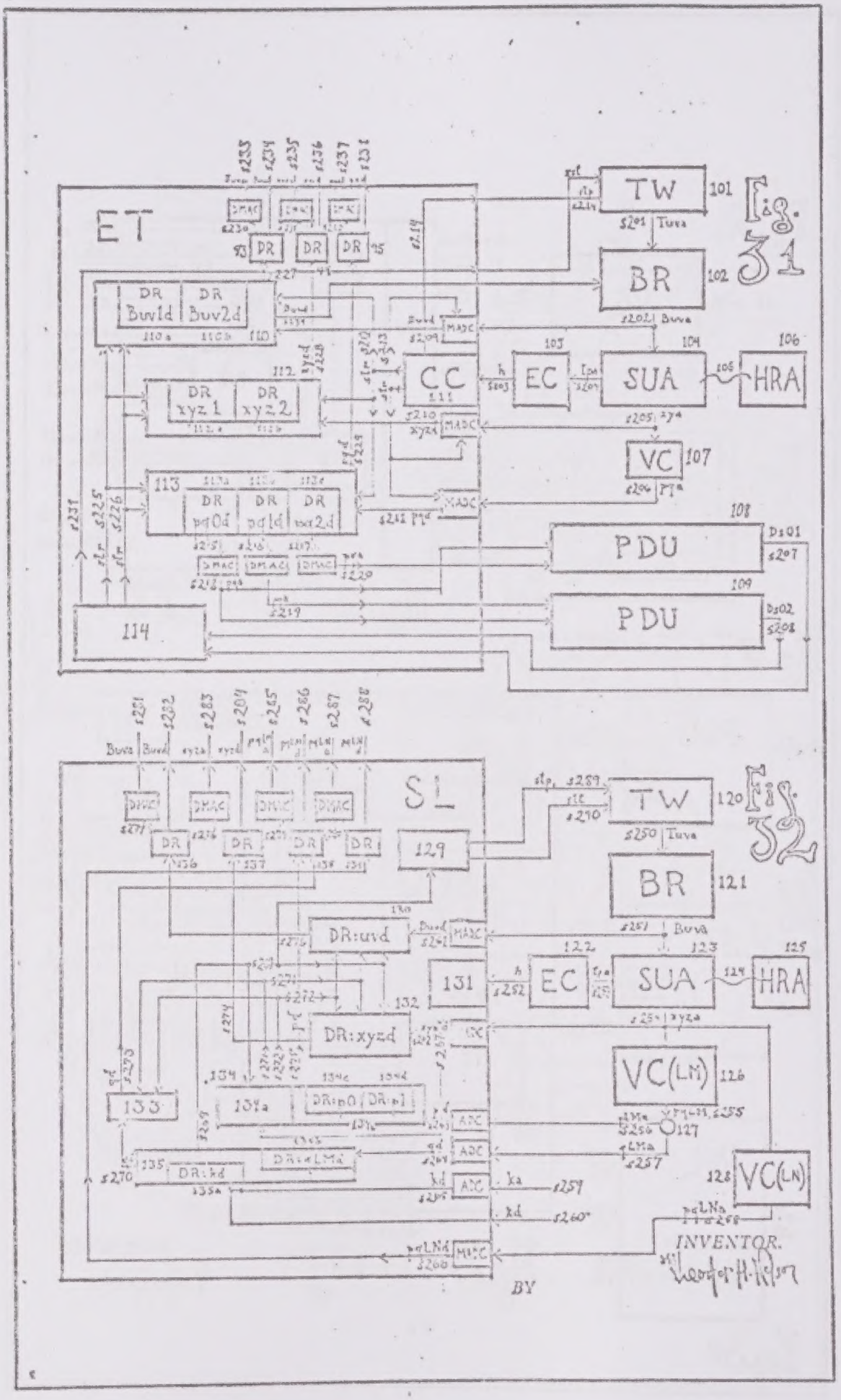
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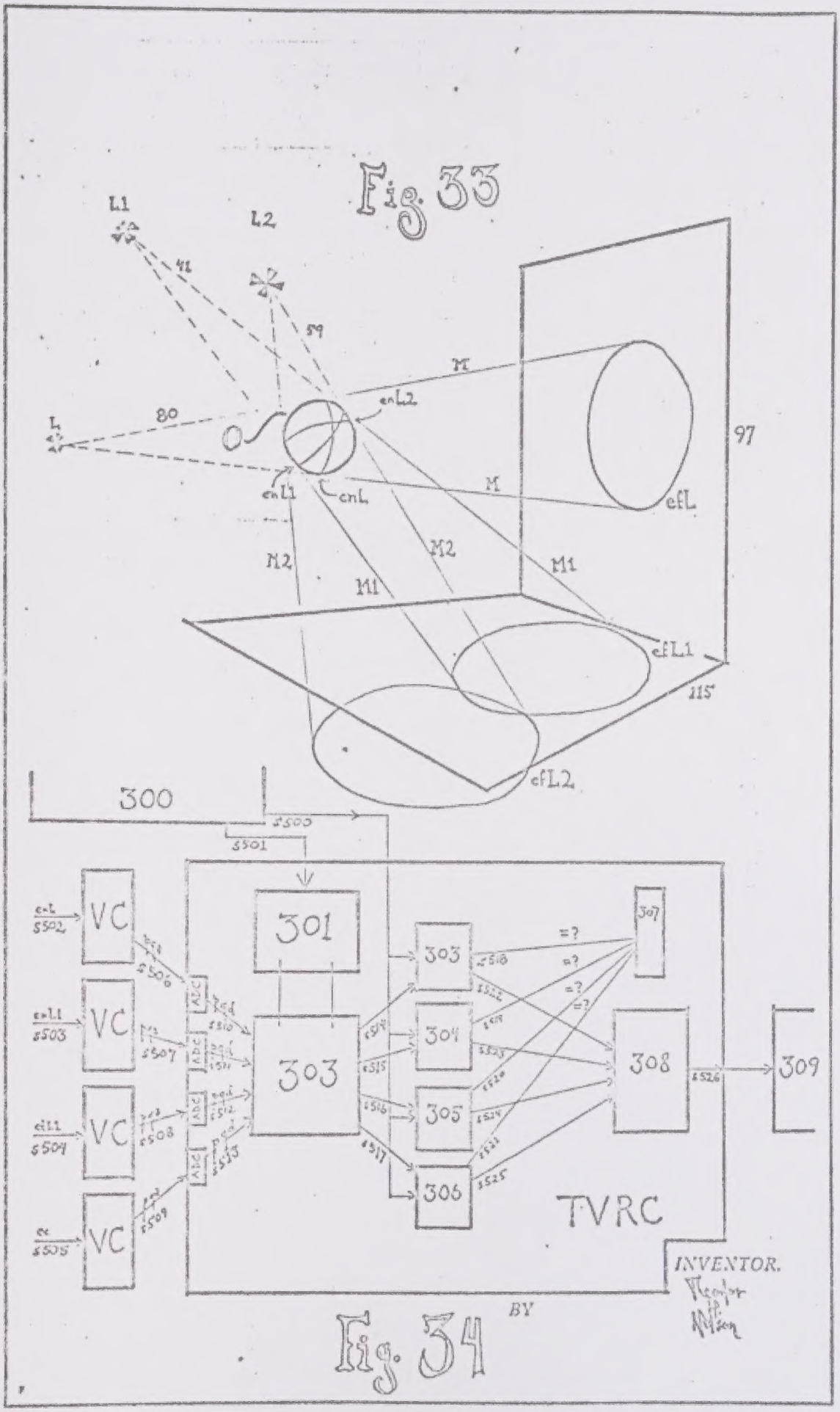
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BY
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=== THE SCENE MACHINE: AN INTRODUCTION

Some might consider this an obscure form of technical humor, describing an odd machine that would never be built. But it had a purpose.

This book is a facsimile reproduction of a patent application that I filed in 1971 or 1972 for an unusual computer system-- peculiar hardware and peculiar methods for using it.

In this introduction, which I am writing almost half a century later, I will tell the story briefly, then explain the system. (The story aspect is more fully told in my book POSSIPLEX.)

HERE WAS MY HOPE: From the 1965 annual conference program of the Society of Motion Picture and Television Engineers—

2:45 #28

Realistic Pseudo-Photography by Computer: The Fantasm System

THEODOR H. NELSON, The Nelson Organization, Inc., New York

The Fantasm system is a new alternative for motion-picture and video-tape production. Instead of using the customary scenery and actors, imaginary animated scenes are created with a computer system and photographic film or video tape. This system's output is indistinguishable from ordinary photographs of real people and settings. Scenery, props and actors are created as required. Since the system can produce its own traveling mattes, its contributions may be used to supplement conventional production in foreground, background or both. Sculpture and puppet theaters are used for easy modeling and smooth manipulation. In the production system, "roughs" will probably be made on video tape before going to more expensive high resolution on film. Cost parameters for everything can be completely controllable through the choice of resolution or deletion of material. The objects are stored in the computer only as coordinates of surfaces, color descriptions and other parameters. By appropriate manipulations and calculations, however, the system will handle curves, shadows and specular reflections. All systematic departures from realism can be eliminated.

Was I wrong?

In the nineteen-sixties, only a few people imagined that simulated photography and movies were coming. I was one of them, perhaps the first, and I hoped to be a founder of what would be a new field, a new branch of the movie industry.

My hands were already full. I was obsessed with my ideas for electronic documents, discussed elsewhere. But this idea of simulated photography and realistic animation was in some ways even more exciting, since I considered myself a filmmaker.

I had already been thinking about two-dimensional computer graphics, but the electrifying idea of photorealistic 3D graphics hit me, I believe in February 1961, as I was walking across the Common in Cambridge, Massachusetts.

In that moment I realized that you could represent a 3D scene in some data structure, and then explore it spatially-- simulating a camera's view of the scene, filled in point by point.

(This is now called ray tracing.)

Not being a mathematician, I thought of it spatially. You would somehow represent a 3D structure, and to make a photograph you would simply look down an array of virtual tubes, like soda straws, to see the color of each point you hit. (Actually this is now considered a variant of ray tracing, called "ray casting".)*

> *** From Wikipedia: "This algorithm has since been termed "ray casting". The idea behind ray casting is to shoot rays from the eye, one per pixel, and find the closest object blocking the path of that ray. Think of an image as a screen-door, with each square in the screen being a pixel. This is then the object the eye sees through that pixel. Using the material properties and the effect of the lights in the scene, this algorithm can determine the shading of this object." -- Wikipedia, "Ray Tracing", 2013.10.05.**
>
> **According to the same article, this method was first published by Arthur Appel in 1968, much later than my 1961 discovery. But he published it and I didn't.**

It would be easy to use this method for making pictures of simple geometric shapes, but that would not be very interesting. Making realistic movies of animated faces and bodies, and other rich objects, would be the real challenge.

I assumed that some artist would sculpt a puppet* represented in 3D, and a puppeteer would manipulate it over time. That would be

the artistic problem. The technical problem would be to search these curved surfaces and depict them in detailed perspective.

> *** Now they use the cute term "synthespian", but I think "puppet" is more straightforward.**

This would be so much better than hand animation, I thought. It would look photographic, like George Pal's Puppetoons—but much as I loved Puppetoons, they were clumsy. This method would be unlimited in its realism-- in sharpness, smoothness and perfectability.

Lights and shadows would use a similar method of spatial exploration. So would reflections. But those would come later.

Curvature was the hard part—representing it, exploring it, rendering it.

I became inflamed on this project, working on it hotly in the ensuing months, and figuring out the details, on and on, for a decade. My card files of dated notes are extensive, and probably of historical interest to somebody.

=== GOING PUBLIC

I submitted a several-page preprint on this idea to the national meeting of the Society of Motion Picture and Television Engineers in 1965. It was handed out by the conference, stapled, with an official-looking cover. The title was "Realistic Pseudo-Photography by Computer: The Fantasm System." The summary in the program you already read on page 1.

No doubt there is a copy of the several-page preprint somewhere in my files, but it is not accessible. As a preprint, it was not reviewed, and I find no reference to it on line.

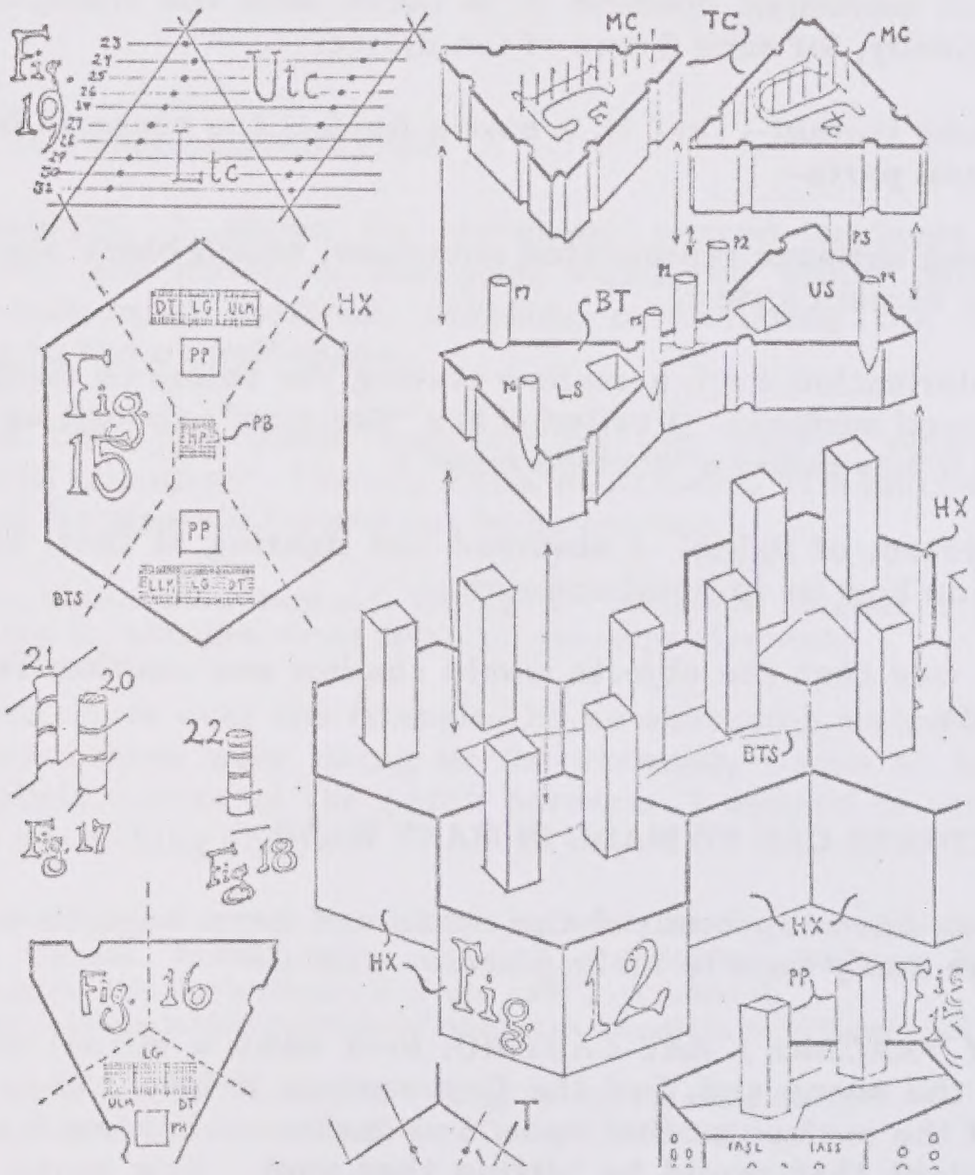
Of historical interest: I believe the preprint was the first document to predict such a technology, and indeed the first document to predict realistic pseudo-photographs of rocketships and dinosaurs, but we won't know till it turns up.

In my oral presentation at the SMPTE conference in Montreal, I tried to demonstrate the principle of ray-tracing with a string to the nose of a volunteer. This did not work very well.

Victor Allen, the editor of the SMPTE Journal, became excited and generous. He offered to publish the full article right away, but this possibility was cut short by his untimely death. I did not even try to contact his successor; the understanding I had with Allen would not be easily re-established. Allen's eager and benevolent support would have made it simple to publish that article, but I had no time to write a complex article of the usual technical kind.

So much for the story. Now for the technicalities.

I will fill the rest of this page with an enticing hardware preview—



=== THE PROBLEMS, ARTISTIC AND TECHNICAL

The artistic problem: **Arrange for a puppet-creator to sculpt a puppet of 3D triangles, and for a puppeteer to manipulate it over time. These are interface issues, which I correctly saw as in principle trivial, though no one I tried to explain it too could see that.***

> *** One of my Vassar students, Sherry Amott, expressed interest in working on the puppets, and indeed (when this system did not materialize) went on to a career at Henson Studios.**

The main technical problem **is to curve over the triangular mesh automatically, for each frame of the movie.**

At any one instant-- that is, a movie frame-- the scene is frozen. It has several parts--

1. Curved surfaces represented somehow, which block one another from the camera's view.

2. A colorization map, somehow stating the colors to assign to the final curved surfaces. (I called this a "flat map"; though as the field evolved it was called a "texture map".)

3. A system of lights. I assumed flat lighting at first, then later worked on how to do point sources.

4. The way that the objects would shadow one another relative to the lights.

=== PICTURES CAN BE MADE IN MANY WAYS

Once you have represented the scene and have ways to explore it, there are many ways to make pictures with it--

1. RAY TRACING / RAY CASTING: look down a virtual soda straw toward the scene and find the first surface it hits. Then find the color of the surface at that spot, and darken or lighten it according to the light that would be hitting that spot. Now move the soda straw repeatedly.

2. EDGE TRACING: It would be nice to find the edge of an object for many purposes—

- matteing (creating a blocking pattern for overlaying pictures)
- shadow calculation
etc.

3. MAKE LINE DRAWINGS OF THE EDGES.

4. TV RASTERS: if you have the edges, you can fill in between them for cartooning.

And various other methods, all possible if we begin with scene representation and exploration.

However, I will concentrate below on the ray tracing / ray casting problem.

=== THE TRIANGULAR METHOD

For simplicity, I chose to represent curved surfaces by 3-dimensional sculptures of triangles, which we would cover with rubbery ballooning surfaces, inflating or deflating the surraces according to the overall shape.

(I figured that you could approximate any curved object as a sculpture of triangles.* Though I had no sources, this mathematical conjecture fortunately turned out to be correct.)

> ***See: "Subdivision Surface", Wikipedia. Of special interest is Kobbelt's method for triangles, dated 2000 (29 years after this work).**

I figured to curve over the triangles by an averaging method.* This is not how others were doing it: for example, Coons at MIT was using explicit curves as the patch borders. I wanted to push past that with something simpler.

> *** Recent papers appear to replicate my work closely, and of course better. See Charles Teorell Loop, "Smooth Subdivision Surfaces Based on Triangles" (Master's thesis, U. Utah, 1987, available at http://research.microsoft.com/en-us/um/people/cloop/thesis.pdf**
>
> **and Vlachos et al, "Curved PN Triangles", 2001, available at http://alex.vlachos.com/graphics/CurvedPNTriangles.pdf**

In the mid-sixties, I got the mathematical formula I needed. Charles Strauss, a mathematician at Brown University, gave me a formula to calculate the hit-point on an inflated triangle for an oncoming ray. That gave me enough mathematics to build this patent application.

=== THE NATURE OF THIS DESIGN

The design in this book represents one approach with several levels—
- representation of shapes by a 3D triangular mesh and nothing more
- curvy surfaces created by inflating or deflating these triangular surfaces. (Herein we use the term "FLATION" for inflation and deflation over the triangles, in any combination.)
- a method of calculating positions on points of these curvy surfaces
- a steering method for exploring the surface
- evaluation methods for judging the resulting points and correcting them
- a special-purpose hybrid computing array of analog processors on a digital baseplate (depicted as triangular circuit blocks that fit among the pegs of the baseplate)
- methods on this hybrid computing array

As far as I know, none of these methods has been pursued further by anyone, except for the triangular methods mentioned above.

=== (THE RIGHT WAY TO DO IT)

When I did this work, in the 1960s, it was not clear that digital calculation would outpace analog calculation, as it has. Back then, analog calculation still was much faster than digital. I took a hybrid approach, holding coordinates digitally and calculating with fast analog circuitry.

It is now clear that the best way to do this is an all-digital approach that calculates the ray intersections with the surfaces. That's how they now do this at Pixar and ILM. But those companies didn't exist in the sixties.*

> ***Nor did the formulas. This was before Bezier patches; Coons was working out patches for representing curvature for designing cars, but I don't think he was ray-tracing.**

=== THIS METHOD: DIGITAL MESH, ANALOG EXPLORATION

This hardware and methods in this book were a legitimate, if quirky, approach to the problem.

1. Representing the Mesh

We represent the triangular 3D mesh in special hardware. The 3D position of each vertex is held in digital registers. (Exceptions to the regular mesh are also handled in the digital hardware.)

2. Basic Coordinates: the Flat Map

The 3D surface has a flat map—a 2D pair of coordinates corresponding to its surface. Thus two numbers specify, and project to, every possible surface point on the flated surface of the curvaceous object.

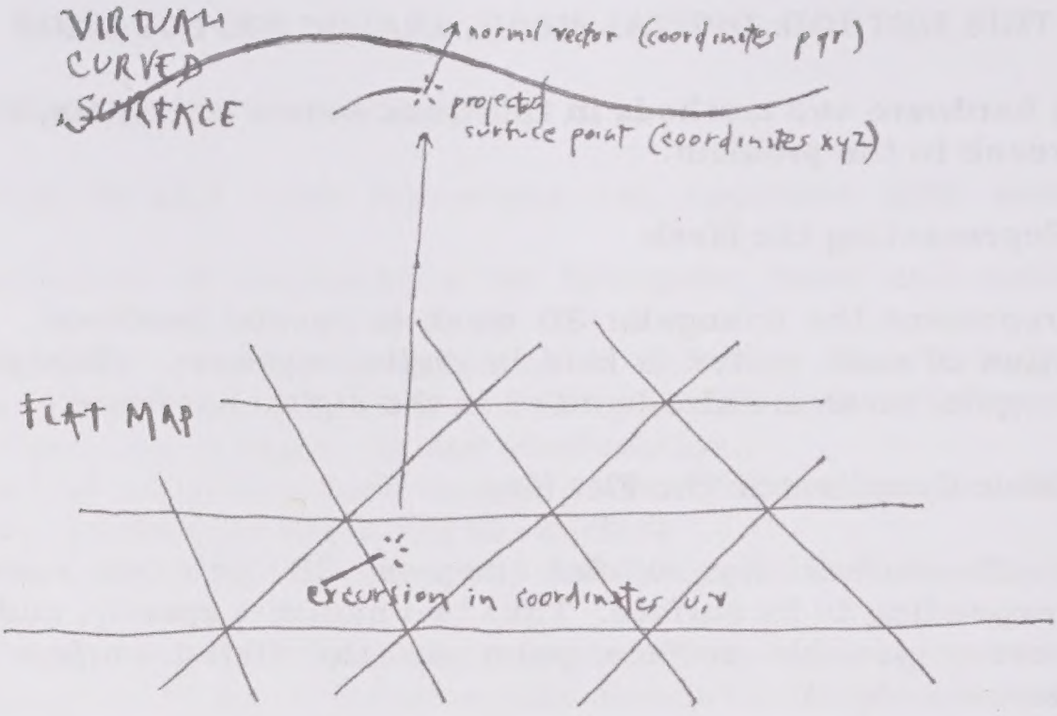
What I called the flat map corresponds to today's "texture map", a picture to apply to the object's surface. However, I was using its 2D coordinates for steering as well.

(I use the term "flat map" for both the steering surface and the picture to be applied. This double usage should not create any confusion.)

3. Projecting to the Curvy Surface from the Flat Map

Think of the flat map as a flat map of Switzerland, and the virtual curvy surface as the mountains of Switzerland.

Each 2D position on this map (call it u,v or just uv) projects to a flated surface position (call it x,y,z or just xyz).



Thus by specifying a series of 2D positions on the flat map, we can explore the corresponding 3D positions on the flated surface.

Such a series of positions we call an EXCURSION. Since we are using analog methods, the series of positions will vary continuously, as a moving spot on both the flat map and the 3D object.

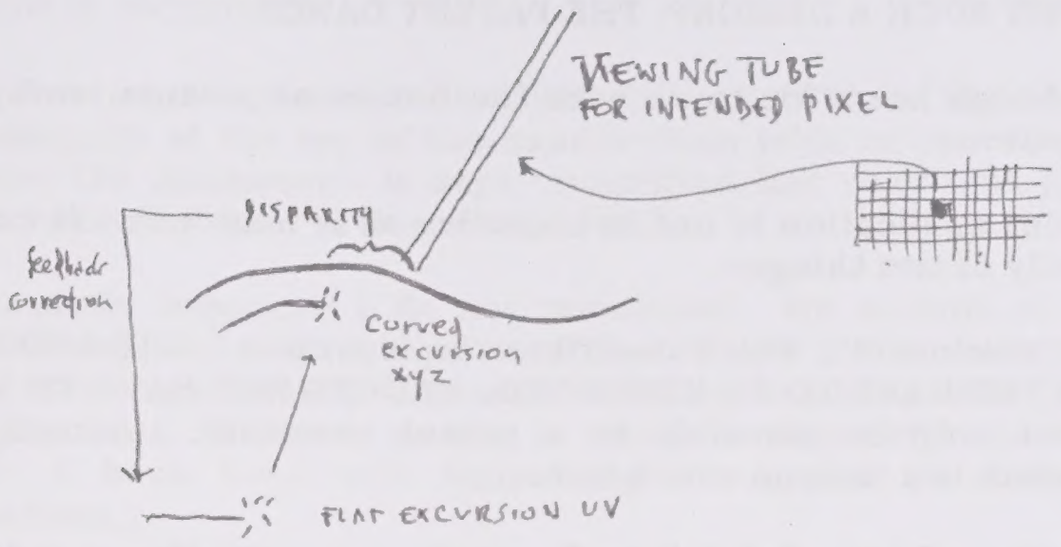
We send a double analog signal, corresponding to a flat map position uv, to the analog processors. (The analog processors-- each representing a triangle of the object—are physical triangular circuit blocks that fit among the pegs of the baseplate; the pegs of the baseplate present the spatial coordinate information to each analog processor block.)

The analog processors calculate the resulting 3D position, xyz, as well as its normal vector, pqr.

The only analog block which responds is the one for the triangle containing the instantaneous value of the excursion signal.

4. Exploring the Mesh: correcting the analog excursion

Thus we explore the surface by a signal uv. The array responds with a signal representing the resulting 3D position xyz.



We then see if that xyz is what we want, either to fulfill a pixel or trace along an edge.

If not, we adjust exploration signal uv.

=== FURTHER DETAILS OF THE SYSTEM

The bulk of this document-- the patent application which follows-- fleshes out this method, in a design which is somewhat fanciful but I believe may be interesting to some.

=== WHY SUCH A DESIGN? THE PATENT DANCE

This design has a lot to do with the nature of patents, and patent applications.

A patent application is not as objective as it may look. It consists basically of two things--

1. A "disclosure", which describes the invention. THE INVENTION DOES NOT HAVE TO BE DEBUGGED. IT DOES NOT HAVE TO WORK. It need only be plausible to a patent examiner. Actually, the disclosure is a rack on which to hang--

2. A list of intended "claims", which you want the examiner to grant.

The claims, if granted by the examiner, are the entire benefit, the teeth of the patent. If a claim is allowed in a patent, that claim grants to the inventor an exclusive right to whatever is described in that claim.

Thus the business of getting a patent is really about staking the claims you hope to get the rights to.

Work back from that. What do you describe? Not necessarily what you would really build, but something that the patent examiner will accept as a basis for the intended claims.*

> *** A very nice historical example: the strange movie cameras designed by Louis Le Prince, the true inventor of the motion picture. These cameras photographed successive movie frames in a checkerboard pattern on a single sheet of film. I am sure he knew this was absurd artistically (since the point of view jumped around), but it provided a basis for the patent claims he was seeking.**

The design of the machine that follows, which I considered somewhat humorous, was intended to establish patent claims of a broader nature in the field of computer graphics-- just what every inventor seeks.

=== HOW IT WOUND UP

This patent application was filed sometime in 1971 or 1972. (Note the ambiguity at the top of the hand-written table of contents that precedes the disclosure-- it says "submitted last year" but alludes also to "amendments" of September 1972.)

What exactly happened I do not remember. My records of these transactions, and the receipt from the Patent Office, are Deeply Filed-- meaning currently unreachable in my archives, though I am sure they exist. (There is no way to check the date with the Patent Office-- I have been told they keep no record of abandoned applications.)

Anyway, as I drew toward completion of this patent application, I was beginning to realize how much competition there was in the area; by the time I had filed the application, I suspected that I was way outgunned.

And I had also gradually realized, as I completed this application, that there was no way I could afford the legal work to press on with it after the first filing. It takes many correspondences and deadlines and arguments with patent examiners before a patent is finally granted, and it takes professional attorneys to handle these tangles. And by now I was broke.

But I finished and filed the application anyway, for the sake of completing the project honorably, and in order that it might be studied later and understood by you.

After which I decided to concentrate on my previous big idea, hypertext.

Theodor Holm Nelson
February 2014

=30=

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PICTORIAL COMPUTING APPARATUS AND PROCESSES INCORPORATING REPRESENTATIONS OF THREE-DIMENSIONAL SUBJECTS

Abstract of the Disclosure

Means including both method and apparatus for representing imaginary or simulated curved three-dimensional objects in a form of computer storage, and by means of various processes carried out upon the representations, for deriving various forms of pictures of said imaginary or simulated three-dimensional objects, including photograph-like half-tone pictures, silhouettes, and line drawings of relative edges and color edges and shadow boundaries; and transmitting said pictures to a variety of output means, including film, television signals and computer display screens. In accordance with the invention, this is accomplished by holding in a representation means data structures representing surfaces of imaginary or simulated three-dimensional objects, and employing upon these data scene-analytic means, which may include means for hunting a particular point in the scene visible through a particular picture-point, means for tracing edges in a scene relative to a particular viewpoint, and means for keeping records of relative edges and relative visibility patterns within a scene; and deriving from various uses of these combined means signals which may be forwarded to said output means, such signals creating the desired pictures.

Background of the Invention

This invention relates to the art of making pictures, and more particularly to an improved method and apparatus for making pictures by automatic computer means.

Pictures are used for a variety of purposes, including teaching, archives, and recreation.

It is to be understood that the term "picture" as it will be used in this application applies not only to whole pictures such as line drawings or photographs, but also to segments or parts of pictures, and in general any two-dimensional analog transform of a part of a view of an object, whether such view be orthographic, perspective, anamorphic or holographic.

Two basic systems are usually employed for making pictures, hand artwork and photography. Disadvantages of hand artwork are high cost, slowness and lack of realism. Disadvantages of photography are high cost, and the expense and obstreperousness of subjects.

Previous computer systems for making pictures are principally concerned with line drawings of non-curved objects. Certain well-known computer picture systems, such as DAC-I, make line drawings of curved objects but do so by calculating a spaced succession of values along curves or meridians of interest on an object.

Previous computer half-tone systems, particularly that of Wylie et al. at the University of Utah, have been restricted to objects made of flat surfaces or polyhedra, without shadow.

It is to improve computer line drawings of curved objects, and to improve half-tone computer renderings of objects by the addition of curvature, shadow and other realistic features, that this invention has been developed.

Summary of the Invention

It is with the above problems and considerations in mind that the present improved picture-making system has been evolved. It is accordingly among the primary objects of this invention to provide means, including both machines and processes usable with these machines or surrogates, permitting such pictures to be made.

The general object is to create a system that will store data identifying a three-dimensional scene, as a system of positional coordinates and the like, and permit complex and comparatively realistic pictures automatically to be made of the scene, including those having the appearance of photography.

These and other objects of the invention, which will become hereafter more apparent, are achieved by representation means and scene analysis means for presenting a three-dimensional surface, and analyzing the scene containing it, said means comprising: 1) an array of representation cells in which are distributed information representations of the positions and shape of the surface sections of an object to be presented; 2) an array of computing units related to the array of representation cells responding to particular query signals; 3) a means here referred to as a "braider," which formulates the query signals on request from certain exploration means; 4) a means here referred to as a "view calculator," which reveals the projected position in some picture or view of a signal representing a point in space on some picture or view; 5) a means here referred to as a "homing unit," which finds points on the represented object which fall on specific points of pictures of the scene of represented objects as seen by the view calculator; 6) a means here referred to as an "edgetracer," which finds edges on the represented object in some view as seen by the view calculator; 7) a means here referred to as a "slicer," which finds contours on the represented object which lie on a straight line as seen from

some viewpoint by the view calculator; 8) a color system, which translates a braider query setting to a specific color on the object, 9) what shall for the purposes of this application be called a mantle list, being a means keeping track of the edges of visibility of objects within the scene relative to a light or point of view in the scene, and 10) what shall for the purposes of this application be called the encounter list, which being a means keeping track of the edges of objects to be encountered in a specific picture to be made.

Line drawings of silhouettes and edges are produced by transmitting output signals from edgetracer to view calculator. Line drawings of upper and lower shadow edges are produced by transmitting signals from edgetracer relative to light to view calculator relative to viewer. Halftone pictures are produced by setting homing unit respectively to successive points in picture, finding point on represented object corresponding to picture-point as seen by view calculator, sending flat coordinates of found point to color system, placing corresponding color-point or grey point in corresponding picture-point. Halftone pictures are also produced by selecting random or pseudo-random points on represented object and transferring corresponding color-point or grey-point to corresponding point on picture as determined by view calculator. Television pictures are produced by following television raster sweep with homing unit and transferring a stream of corresponding color-points to the brightness system. Television pictures are also produced by gating television brightness as raster sweep crosses values on encounter list. Three-dimensional pictures are produced by conducting process from two or more separate points of view.

A feature of the embodiment of the invention described here, but not of all embodiments, is that all surfaces are to be represented by division into spatial triangles or facets, and closed curved surfaces are created automatically over the multi-faceted sculptures by computing units each responsible for curving over one facet.

Another feature of this embodiment of the invention is the use of a freely variable exploratory signal representing a point in a three-dimensional scene, which in its variations represents movement of a point upon the surface of a represented object, and the transference to a two-dimensional picture of the instantaneous position of such a point as seen from a specific vantage.

Another feature of this embodiment of the invention resides in the fact that a continuous exploration of a surface section may take place by analog computation, permitting infinitesimal adjustments without cessation of representation signals.

A feature of the invention resides in the fact that pluralities of computing cells may be aggregated into extremely large arrays, and signals to and from them so merged and blended that the array of cells will respond electrically like a single cell.

Another feature of the invention resides in the array's capability of simultaneously performing different operations in the picture-making chain of activities, being electrically subdivided for this purpose into more than one section, with control signals passing from, or passing from means related to, particular sections of the array so subdivided, to one or more other sections of the array so subdivided to guide the activities therein.

Another feature of the invention resides in the provision

of automatic exception-handling procedures permitting aberrant interconnections among reference points in the surface data which

3 do not conform to the triangular mesh structure of the facet system.

Brief Description of the Drawings

The specific details of apparatus and methods suitable for practicing the method of this invention, and their mode of functioning, will be described in full, clear, concise, and exact terms in conjunction with the accompanying drawings, wherein:

FIG. 1 is a perspective detail view illustrating a polyhedron of triangles, having the standard mesh connections, which has been configured into the shape of a nose.

FIG. 2 is a cross-sectional schematic view of the elements of curvature, showing facets, influence planes and curved surface shell.

FIG. 3 is a schematic drawing showing the standard mesh of interconnections.

FIG. 4 is a schematic drawing showing the three mesh dimensions R, S and T and the six mesh directions a, b, c, d, e and f.

FIG. 5 is a schematic topological diagram illustrating the coincident superposition of hexagon and "bow-tie" mathematical wallpaper patterns.

FIG. 6 is an abstract schematic drawing showing the relative labelling of mesh-points, edges and triangles in the mesh surrounding an arbitrary point @.

FIG. 7 is an abstract schematic drawing showing the orientation in the general triangle of inpointing covariate dimensions ⅈ, ⅉ and ⅊.

FIG. 8 is an abstract schematic drawing of wide-span absolute surface dimensions u, v and w over an array of triangles, facets or tricells, showing intersecting corridors of equal u and v values. This illustration also distinguishes wide-span surface dimensions

u, v and w from mesh dimensions R, S and T.

FIG. 9 is an abstract schematic diagram illustrating the differences between wide-span bi-trivariate coordinate surface uv(w) and inpointing trivariate coordinates $\not{u}$, $\not{v}$, $\not{w}$ in an upper and a lower facet.

FIG. 10 is a diagram showing the Bu half of the oscillating "braid code" Buv of surface coordinate controls across 8 spans of u values, specifying the Bu voltages; the corresponding diagram for Bv would be identical.

FIG. 11 is a schematic diagram of a tricell array showing bands of response to braid Buv and sample sensitive array elements.

FIG. 12 is an exploded orthographic elevational view of a five-unit array of hexes, a bowtie converter unit, and an upper and lower tricell surface generation unit, indicating their method of physical intercoupling.

FIG. 13 is a perspective elevational view of a hex, showing the photoluminescent elements and light receptors on the sides.

FIG. 14 is a schematic bottom plan view of a hex, showing the electrical connections at its base.

FIG. 15 is a top plan view looking down at the surface of a hex, showing its optical output registers.

FIG. 16 is a bottom plan view looking up at the lower surface of a bowtie, showing its photoreceptors.

FIG. 17 is a perspective elevational view of a connecting post of the type arising from sides of the bowtie, and the method of engagement of its signal contacts with receptor shoes within a matching groove of the tricell.

FIG. 18 is a perspective elevational view showing a connecting post having five signal contacts, of the type emplaced at the center of the bowtie.

FIG. 19 is a top plan view showing the wired interconnections between individual tricells.

FIG. 20 is a schematic top plan view showing the signal sources relating to an individual bowtie.

FIG. 21 is a schematic drawing showing the positions of aperture bits in a typical aperture pattern, and the tricells which are receptive as a consequence.

FIG. 22 is a schematic drawing showing the interconnections of facets in an exception to the conventional mesh pattern of FIG. 3.

FIG. 23 is a schematic drawing showing the accommodation of the exceptional pattern shown in FIG. 22 within the triangular array by means of mesh exception logic.

FIG. 24 is a schematic drawing showing the inputs and output of a view calculator.

FIG. 25 is a schematic drawing showing the component parts and signal paths of the braider.

FIG. 26 is a schematic drawing showing the component parts and signal paths of the twirler.

FIG. 27 is a schematic drawing showing the component parts and signal paths of the Pythagorean distance unit.

FIG. 28 is a schematic drawing showing the component parts and signal paths of the homing unit.

FIG. 29 is a schematic drawing showing the component parts and signal paths of the edge checker.

FIG. 30 is a schematic drawing showing the component parts and signal paths of the reflector.

FIG. 31 is a schematic drawing showing the component parts and signal paths of the edgetracer.

FIG. 32 is a schematic drawing showing the component parts and signal paths of the slicer.

FIG. 33 is a perspective elevational schematic drawing of a hypothetical scene, showing a lookout L, lights L1 and L2, an object, and its shadow and visibility edges.

FIG. 34 is a schematic drawing showing the component parts and the signal paths of the TV raster controller.

Description of the Preferred Embodiment

Referring now more particularly to the drawings, like letters and numerals in the various figures will be employed to designate like parts.

This invention consists of methods for representing curved objects in a form of computer storage, and of creating pictures of these objects by means of various processes carried out upon the representations.

While various representation schemes are possible within the scope of this invention, the present embodiment represents curved objects in data structures composed of triangles interconnected in three-dimensional space, or as they shall hereafter be called, "facets." We consider all objects in a scene to be polyhedra constructed of such facets, puttied over for smoothness, as may best be seen in FIG. 1, showing a nose so represented. The means described herein will generate all other points on a closed, curved, smooth connecting surface in which these reference points are embedded, and the resulting pictures will appear to be photographs or other pictures of solid objects.

The subject-matter of pictures to be made in this fashion is to consist of the representation of three-dimensional objects, sculptures or puppets, transformed into data. How these data are acquired is of no importance, although I suggest that it should be sculpted by a human artist or craftsman sitting at a computer display screen such as the IBM 2250. An appropriate computer program, such as Timothy Johnson's well-known "3-D Sketchpad" at Lincoln Laboratory, will allow him to position points in a 3-dimensional space seen on the screen, and by comparing different views and

working with light-pen to communicate with the program, he may change the three-dimensional points in a scene to his satisfaction until all are appropriately positioned. Appropriate surface data may also be produced by automatic means, as by derivation from contour maps.

The system described here, a particular embodiment of the general invention, produces images of smoothly curved surfaces which have been created as a shell, skin or bubble over all the points whose positions are given at the outset, which reference points act as the respective corner-points of the different facets. Over or under each facet, and sharing in this embodiment its corner points and edges, is a curved shell or surface section, as best may be seen in FIG. 2, a schematic cross-section view of a central facet CF, two adjacent facets A1 and A2, two averaging or influence planes If1 and If2, and curved shell or bubble over them SH, facet-point FP, raised influence points RIP1 on If1 and RIP2 on If2, and averaged surface-point $SP_{x,y,z}$.

In the present embodiment the data used to represent the curved surface consist only of the three-dimensional coordinates of the facet corners, hereinafter called "reference points," and the specifications of what reference points are connected to what others by facet edges, hereinafter called "connections." This surface system represents truly curved surfaces, rather than approximations by points or polyhedra, and requires no further data for the production of the surfaces than the spatial coordinates and interconnections of the reference points. In general these connections will conform to a certain pattern familiar from the game of Chinese checkers, hereinafter called "the triangular mesh" or "the mesh," seen in FIG. 3. This basic pattern, considered abstractly,

continues indefinitely in all directions. It is assumed that the original reference-point array has been arranged in the necessary triangular mesh by those in charge of editing the data. While exceptions are necessary, we will consider these not to be typical.

We distinguish between "facets" in the scene-space and triangles in the mesh, the corresponding figures without respect to their three-dimensional position or the lengths of their sides. The connective pattern is identical considered either way, whether configured into a three-dimensional shape with irregular sized facets, as in FIG. 1, or spread out flat in a schematic equilateral representation as in FIG. 3. This connective pattern has no relation to the relative distances between points, but only their connective structure. By convention we shall define three dimensions and six directions in the mesh, dimensions R, S and T and directions a, b, c, d, e, f, as will be seen schematically in FIG. 4. These directions apply along mesh connections whether in three-dimensional space as in FIG. 1 or the abstracted pattern as in FIG. 3.

In the present embodiment, the data so representing a surface is physically distributed through an array of cells physically mapping the triangular mesh, which shall hereinafter be called "the array." The data distributed in it, or other data arranged in a form suitable for distribution in the array, we shall call a "data web" or "web of data."

The array of cells through which this data web is to be distributed all conforms to the triangular mesh, but owing to quirks of the design its parts have different interlocking physical shapes, as will be seen in FIG. 12. Since in this embodiment the computation of a curved shell-section from the data for a particular facet requires data from three ad-

jacent facets, as will be shown, it was found convenient in the present design to make the computation cell triangular in shape TC. This computation cell will hereafter in this application be called the "tricell." However, this was not an appropriate shape for the basic representation unit. Since the basic representation cell of the array is to represent coordinates and data referring to a single reference point shared by six facets, this cell is hexagonal in shape HX, as the basic pattern of interlocking hexagons is the complement (or graph dual) of the triangular mesh. Indeed, it has been found convenient for the present implementation to use this hexagonal cell, hereinafter called "holding register unit" or "hex," to hold data for two facets. This is because there are twice as many triangles as corner-points in the mesh. Thus we may assign two triangles exclusively to each mesh-point and its hex. By convention here we will assign to a given point the triangles above and below that point, and call them that point's upper and lower triangle, respectively, as seen in FIG. 6 Up and Lo.
A third type of cell in the array reflects this relationship, being mounted on the hex and having mounted on it two tricells, as will be likewise seen in FIG. 12. This device shall be called the "conversion unit" or "bow-tie" BT, due to its bow-tie or hourglass shape. As may be seen in FIG. 5, the interlocking bow-tie pattern matches the hexes and triangles in the mesh, with none left over.

Our terminology for elements of the mesh is in accordance with the arrangement of significant elements in the surface curvature system. In FIG. 6 we may see the labelling of points, edges and triangles or facets in the mesh, all with respect to an arbitrarily selected reference point @ (a letter which may be called "at").

A reference point, considered as a starting point, we call @. Another reference point is referred to by an expression beginning with @ and then concatenating the directions of movement or turn (a, b, c, d, e, f in FIG. 4) to get to that point from @. Examples: @a, @b, @aaa, @ef. An expression for a point contains one @-symbol. A line is referred to by its two endpoints in the above notation. Since there is no ambiguity, the endpoints can be concatenated. Examples: line @@a, line @b@c. An expression for a line contains two @-symbols. A triangle is referred to by its three corner points in the above notation. Since there is no ambiguity, the points can be concatenated. Examples: triangle @a@ab@b, triangle @@b@c. An expression for a triangle contains three @-symbols.

However, it will usually be more convenient to refer to edges and triangles in the shortened form seen in FIG. 6: edge @@a is 1, @a@b is 2, @@b is 3, @@d is 4, @d@e is 5, @@e is 6. The upper triangle of @ is Up, surrounded by three adjacent triangles Up1, Up2, Up3; the lower triangle of @ is Lo, surrounded by three adjacent triangles Lo4, Lo5, Lo6. If it is necessary to speak out of context of one or more arbitrary points, the symbols @g, @h, @i are used, and may be concatenated like the others.

To specify a point within a triangle or upon a facet, we use trivariate coordinate dimensions, shown in FIGS. 7 and 8. In trivariate dimensions, any two dimensions of the three are independent, but the third may be computed from the other two, regardless of which two are originally given. This may best be seen in FIG. 7, in which dimensions μ, ν, ρ cross one another; if the distance from a base to its opposite apex is considered to be 100,

then the three measurements of any point in the triangle on the three dimensions %, %, % always sum to 100. Thus given measurements % and %, the third % may always be computed.

In order to provide continuity among facets, we use in this embodiment a large-scale trivariate coordinate scheme consistent over the entire mesh, as will be seen in FIG. 8, where dimensions u, v and w continue across the mesh over many facets. (That these surface dimensions are distinct from mesh edge dimensions R, S, T also shown, may be seen from the illustration.) Shaded lanes =u, =v indicate directions in this whole tissue having equal measurements of u and v respectively. The distance between apex and base in each dimension of each triangle is assigned a value of 1 in this control system.

The necessary conversions to convert from these large-scale trivariate coordinates to the coordinates of particular facets are indicated schematically in FIG. 9, showing that to obtain inpointing trivariate coordinates in an upper facet w must be subtracted from 1 to obtain %, and in a lower facet u and v must each be subtracted from 1 to obtain % and %.

In this embodiment, using the large-scale coordinates shown in FIG. 8, u and v are selected as the basic describing and controlling variables, and w is automatically calculated therefrom. Thus any point on any facet has coordinate measurements (u, v, w), which we hereafter abbreviate as uvw, but these are determined by two independent measurements uv. Thus we call any facet-point uv.

According to the curvature system in this embodiment, point uv is raised by mathematical procedures to a point on a curved shell $\overset{SH}{\wedge}$ associated with its facet, which we shall call the "surface-point," as shown schematically in FIG. 2 SP. Since the position of this point in the scene's three-dimensional coordinates

x, y, z is of significance for the system's operation, we designate this surface-point xyz. Such a surface-point is calculated from u and v, and changes in the surface-point are calculated from changes in u and v. Thus we call u and v the control variables, and the uv signal on which all calculations are based we call the control signal.

To specify the unique position of a facet-point within the entire surface tissue or data web, an additional specification of a particular facet must be added to uv. The resulting full specification we call Absolute uv, or Auv. However, for practical purposes it is shortened and translated to what we call Braided uv, or Buv, partially illustrated in FIG. 10, a mixed signal which selects a particular facet from among a number of possible facets.

A surface point is calculated by a mathematical process which extracts control variables uv from their embedded position in this multi-component control signal Buv, calculates dependent control variable w from them, converts control signals uvw to their proportional converted values Cuvw on a facet having specific measurements, locates them as localized values Luvw in the correct spatial position corresponding in the spatial triangle to their position in the abstract equilateral triangle, and inserts them in a set of formulas, procedures and data respective to the particular facet and its surroundings, which are used to calculate surface-point xyz.

These general formulas take the coordinates of a localized point on a facet in the scene and the orientation of that facet and the adjacent three facets, and computes a raised or lowered point on a curved surface smoothed through all reference points of the object.

In FIG. 2 we see this raising process applied to a facet-point FP on a central facet CF. The facet-point FP is raised at right angles from central facet CF to a point xyz on surface-shell SH by a series of calculations. These calculations take into account the orientations of the adjacent facets, A1 and A2 being shown, by averaging the orientations of the adjacent and central facets to hypothetical facets we may call "influence facets," If1 and If2 being shown. The facet-point FP is elevated toward its corresponding raised influence points on these influence facets RIP1, RIP2, but these are averaged according to a function which changes as a curve depending on the position of FP on CF.

The general formulas are as follows. Given are facet-point Luvw, the orientation of the central facet expressed as unit normal vector NmCF and the orientations of the adjacent facets expressed as unit normal vectors NmAF1, NmAF2, NmAF3. The orientation of the central facet is averaged in turn with the orientations of each of the three adjacent facets, yielding the orientations of "influence planes" If1, If2, If3, expressed also as unit normal vectors, by the application of the formula

$$IfN = \frac{NmCF + NmAFN}{2}$$

where NmCF is the unit normal vector of the central facet, NmAFN is the unit normal vector of the nth adjacent facet and IfN is the unit normal vector of the influence plane shared by the central facet and the nth adjacent facet, as seen in FIG. 2, If1 and If2.

For each of these three influence planes, an intersection point is calculated with a vertical extension of facet-point Luvw (FP in FIG. 2) normal to the central facet CF. In FIG. 2 two of these intersections may be seen RIP1, RIP2. This calculation is done in two stages, first by solving for influence coefficient IC for each of the three influence planes by the formula

(Luvw + IC times NmCF - ©g) · IfN = 0

where the dot indicates vector dot product, "times" indicates ordinary multiplication, ©g is the coordinate vector of either of the two vertices shared by the central facet and adjacent facet N. The influence coefficients are then used to find the raised intersection points RIP, two being shown in FIG. 2, RIP1 and RIP2, by using the following formula for each influence plane:

RIP = Luvw + IC times NmCF

where RIP is the desired raised influence point.

A weighted average of these three influence points is then found, employing as its averaging method a square root of sum of squares, where the weights are proportional to the relative position in the facet of facet-point Luvw. Each weight is found by the formula

$$W = \frac{1}{1 - \frac{D - d}{D}}$$

where d is the distance of the facet-point from a given edge, equivalent to converted control variable Cu, Cv or Cw, D is the distance of the opposite vertex of the central facet from that same edge, and W is the desired weight. The weighted average, or final surface point, is then

$$xyz = \frac{W1RIP1 + W2RIP2 + W3RIP3}{W1 + W2 + W3}$$

A similar formula yields the tangent at this surface point:

$$tp = \frac{W1\ If1 + W2\ If2 + W3\ If3}{W1 + W2 + W3}$$

where tp is the tangent plane at the surface point, expressed as a unit normal vector. We will thus also refer to it as the "tangent perpendicular," since the normal vector is perpendicular to a plane.

These formulas are rendered slightly more complex in the machine design by the distinction between upper and lower facets, and the need of extracting from control braid Buv the converted and localized facet coordinates Cuvw and Luvw, and assuring that only one tricell responds, and the presence in one hex of data for two facets.

The surface method just described produces the representation of a truly curved surface shell over the entire network of reference points. It has, however, the disadvantage of a sort of "quilted" texture, whereby the surface shell touches the surface not only at the reference points, but also along the straight edges between reference points. The resulting depicted surface resembles a quilted texture, of curved tufts hemmed down by straight edges. However, various improvements may be used, in other embodiments than the principal one described, to mollify this disadvantage. These differ mainly in their surface methods. Surface methods more satisfactory in this regard may produce or utilize bows or arches representing or showing curves between these reference points, thus eliminating the embedded straight lines between reference points.

An example of a fuller surface method which eliminates the disadvantages of the surface method in this present embodiment is as follows.

To eliminate the "quilting" and provide a wholly curved surface, the principal aspect of the formulae which is changed concerns tilting the normal vector at the facet-point Luvw. We shall examine this method both for triangular facets, as incorporated in the present embodiment, and for general polygons, as might be incorporated in other embodiments of this invention.

For triangular facets, d and D are calculated as before. A varying "tilt" is calculated, however, for any facet-point uvw. This shall be considered to be the unit normal at point uvw. A formula is:

$$Nm(uv) = \frac{d1If1 + d2If2 + d3If3}{d1 + d2 + d3}$$

The formulas for IC, RIP and W may be as before. An acceptable formula for xyz is:

$$xyz = \frac{W1RIP1 + W2RIP2 + W3RIP3}{W1 + W2 + W3}$$

An acceptable formula for tp is:

$$tp = \frac{W1If1 + W2If2 + W3If3}{W1 + W2 + W3}$$

These non-quilted formulas may be extended to the general polygon of more than three edges, with or without a regular mesh or mathematical wallpaper pattern, being in either case embodiments conforming to this invention. For such an application distances d may be found in the conventional geometric fashion for all sides. The tilt at a facet-point (which we here temporarily call P instead of uvw, there being more than three respective distances of the point from the edges) is given by the formula

$$NmP = \frac{d1If1 + d2If2 + d3If3 + \ldots + dNIfN}{\Sigma d}$$

A formula for the respective ICs is

$$(Luvw + IC \text{ times } NmP) \cdot IfM = 0$$

for M = 1, 2, ... N. The formulas for RIP and W may be as before for individual RIPs and weights, one per side. A formula for the surface-point is then

$$xyz = \frac{W1RIP1 + \ldots + W(N)RIP(N)}{\Sigma W}$$

and a formula for the normal at the surface-point is:

$$tp = \frac{W1If1 + \ldots + W(N)If(N)}{\Sigma W}$$

These variant surface-generation systems furnish a more satisfactory surface, and while this invention is by no means limited to them, they are included here to illustrate the generality of this invention's coverage. Owing to the possible varieties of algebraic approximation and transformation, many other formulas may be derived having the equivalent effect, also within the scope of this invention.

However, for the remainder of this application, the earlier quilted method will be used for simplicity's sake. (An exception employing storage tubes will be explicitly so introduced.)

To further this discussion, it is necessary to enlarge the system of notation, in order to be able to specify parts of a scene and signals relating to that scene.

In the notation to be used, a succession of letters does not imply multiplication, as in algebra. Rather, its components represent elements in the system in concatenation. Concatenation in this notation may use both prefixes and suffixes.

Certain prefixes are functions, for example NmF, the unit normal vector of a facet (e.g. NmUp, NmLo). In general, however, prefixes and suffixes may be any expression; for example NmUp may be suffixed to x, viz. xNmUp, to refer to the x component of NmUp. In general any symbolic expression may be attached to any other expression by mere concatenation, the only restriction being one of reasonable meaning.

Such concatenation shall subsume the conventional subscripting function. By convention now established, we shall introduce numerical suffixes (having the usual meaning of numerical subscripts) which are concatenated with the symbols they modify, e.g. x1, L2. Such subscript suffixes are to be full-sized numbers and capital letters. In the few cases where this practice might introduce ambiguity, we will put them in parentheses.

Two classes of symbols must be distinguished, those representing scenes and those representing signals, and their interrelationship made clear.

A number of terms and notational conventions are associated with a scene and its parts, as will be seen in FIG. 33.

Certain points in space representing a camera viewpoint L and lights L1 and L2 are in important respects similar; accordingly we call L the "lookout" to justify the use of the letter L. L1, L2, L3, L4 shall be lights; LN shall mean any L, including L, L1, L2, L3, L4; LM shall mean any L distinct from LN; and to refer to an arbitrary light, either L1, L2, L3 or L4, we shall say "LN-except-L."

View-coordinates p and q represent the two-dimensional coordinates of a view of a scene from LN. The term pqL accordingly refers to the coordinates of a point in a view or picture seen from L, and similarly for pqLN-except-L, meaning the coordinates of the scene viewed from a light. It should be understood that while pq represents a point on a view of the scene-space from LN, it concomitantly represents a line or ray through the three-dimensional scene-space passing through points LN and pq and projecting to those points throughout its length; a "sight-line."

The term "en" shall mean the near edge (edge, near) of an object O as seen from a point in or around a scene. The term en may be subscripted with reference to its origin L, L1, L2 to further specify it enL,,enL1, enL2. Similarly, the term "ef" shall refer to the corresponding far edge obscured by object O relative to point L, L1, L2, being thus subscripted efL, efL1, efL2. Edges of color may also exist, being called ec (edge, color), but these are not LN-subscripted, as they are not relative to LN. Edges ec are not shown in the drawing.

A mantle M is the system of invisible surfaces extending in space between enLN and efLN. In FIG. 33 are shown mantles M, M1, M2, which take their numerical suffixes from their points of origin L, L1, L2. Each mantle has as its origin of radiation a point LN and its shape is defined by the contour (and position) of the object on which en occurs. The shape of ef is derivative of the shape of en.

The mantle M of L represents the boundary between what is visible and invisible to an observer at L; the mantle M(LN-except-L) represents the boundary between what is illuminated and what is in shadow. As the mantle can take complex forms, methods for describing and employing it will be expounded later.

A "probe" shall be taken to mean a point in scene-space which is generated by the system as part of any process. (The probe consists not only of the surface-point xyz, but equivalently of any of its transformations uv, Buv, Tuv, Luvw, etc., as will be discussed below.)

An "excursion" shall refer to the successive positions of a probe moving through a scene, or to the system's act of moving the probe through successive positions of the scene. (The excursion consists not only of the succession of movements of xyz, but accordingly of the movements of any of its transformations uv, Buv, Tuv, etc., as will be discussed below.)

This system employs a number of types of signal, both analog and digital, frequently carried along multiple conductors in parallel compound form.

Signals we always represent with lower-case letters, e.g. uv, xyz.

The main signals in this system are compound signals representing several quantities or numbers which, taken together, form a meaningful unit. The principal such compound signals of this system are uv, xyz, tp, and pq, already introduced.

A line consisting of a plurality of conductors carrying such a compound signal we call a "multiline." Connections between such multilines which maintain the distinctness of their separate strands we call "multiconnectors;" a post serving as such a connector (as in FIGS. 17, 18) we call here a "multipost."

A "multiconverter" is a device that converts from an analog multiline to a digital multiline, in which case it is called a multi-analog-to-digital converter (MADC), or a device that converts from a digital multiline to an analog multiline, in which case it is called a multi-digital-to-analog converter (MDAC).

Digital registers (abbreviated DR) shall be referred to simply by their customary contents, and a separate register for each separate strand or constituent will be understood.

The suffix "a" shall be used to distinguish an analog signal, the suffix "d" shall be used to distinguish a digital signal (there being due to context no possibility of confusion with mesh directions a and d).

The letter "h" shall refer to a signal signifying a hit, the

letter "m" shall refer to a signal signifying a miss.

Signal rfl represents a ray or sight-line in the scene-space which is reflected from an object. Thus rflxyzLN refers to the reflection from point xyz of a ray from LN.

The compound signals (particularly uv) are at times modified and transformed in various ways. We use capital-letter prefixes to indicate the particular transformations. The transformations include "B" for braided, "D" for difference, "T" for twirled, all these to be explained. (These transformations of compound signals are distinct from certain compound quantities or functions employed by the curvature system. These are non-transforming entities which have been given names beginning with a two-letter prefix ((first an uppercase letter, than a lower)), e.g.g. Lg3, Ds@5.)

We may now generalize our concatenative notation for signals. The signal names and their appropriate transformations, conversions, derivations and dependencies may be concatenated to any length: for example, pqL3efL, meaning the pq from L3 of a probe or excursion of ef with respect to L. The concatenation is in descending order of recency, with the most recent conversion or derivation first and successively more remote ones thereafter.

With these notational preliminaries understood, we may consider the controlling or scene-searching means employed in this embodiment of the invention. The surface information is constant during the making of a single picture (or frame for a motion picture) in this embodiment of the invention. Various surface-points xyz of the represented objects in a scene are probed during the processes of this invention.

In the process of determining these surface-points xyz, the controlling information is given by uv, which we may call the "flat-point" on the facet (FIG. 2, FP) which projects to the surface-point xyz (as shown in FIG. 2) by means described in this application. Therefore the suitable varying of uv, and directing these quantities to the proper facet, is an important aspect of the system in the present embodiment. For this purpose the "control braid" is employed in the present embodiment of the invention.

A probe uv→xyz is controlled by a compound signal which we call the braid Buv, which is a function of control quantities u and v, as may be partly seen in FIG. 10.

The braid performs several functions. First, it may proceed infinitely in four directions (positive and negative u and v), and therefore realizes a movement across the wide-span uv surface of FIG. 8. (We shall henceforth call these wide-span coordinates Auv, for Absolute uv, and refer to their component Absolute u as Au and their component Absolute v as Av.) Second, complex variations and movements between and among cells for surface representation and generation may be effected simply through use of the control

braid. Third, its compound signal permits easy discrimination between four different stages in both dimensions, u and v, providing automatic selection among adjacent tricell units representing a surface. Finally, response to this control braid may be digitally reset by means of the recognizer setting.

The braid Buv, partly seen in FIG. 10, consists of four dependent voltages, u1 and u2 (together called braided u or Bu), which together represent the control quantity Au, and v1 and v2, not shown, together called braided v or Bv) which together represent the control quantity Av. As control quantity Au or Av increases, its two dependent braid voltages (u1 and u2 or v1 and v2) oscillate out of phase between +1.2 volts and -0.2 volts. One of the dependent voltages from each pair is always between +1.0v and 0.0v, while the other is not. This combined analog control signal can proceed infinitely in either a positive or a negative direction. As Au or Av increases or decreases, its braided function passes through four stages, depending on the relation of the two constituents (u1 and u2 or v1 and v2). We may call these stages A, B, C and D, as shown in FIG. 10. Facts necessary for the translation of the code braid to single-facet uvw are shown in the following table.

Bu stage	usable component between 0 and 1	proportionality of usable component	polarity of beyond-threshold component	conversion formula to obtain $\not{u}$
A	u1	direct	+	$\not{u} = u1$
B	u2	inverse	+	$\not{u} = 1-u2$
C	u1	inverse	-	$\not{u} = 1-u1$
D	u2	direct	-	$\not{u} = u2$

Tricells are set to respond to this code braid by means of a code called the "recognizer code," stored in the hex. The same recognizer code is given to corridors of tricells in the array, as shown in FIG. 11, at right angles to dimensions u and v, and cells within these corridors respond equivalently to stimuli of Bu and Bv respectively. As will be seen in FIG. 11, corridors of triangular surface generation units parallel to the arrows have recognizer codes set to respond equivalently to the A, B, C and D ranges of u uA, uB, uC, uD, and likewise in another dimension to the A, B, C and D ranges of v vA, vB, vC, vD. Only a cell at the junction having the right code characteristics will respond to a signal. Thus a Buv signal where Bu is in range uC and Bv is in range vA will cause only two triangular surface generation units to respond 7, 8. The recognizer code, and the means of discriminating between 7 and 8, are discussed as a part of tricell operation.

The braid code of this embodiment provides means for discriminating only among sixteen separate tricell pairs (uA to uD and vA to vD). Further discrimination is afforded by the aperture system, which enables only a subset of cells to respond, generally arranged in a pointless triangle, as in FIG. 21, s; the braid code discriminates among cells within this subset.

We are now prepared to consider all the variations and transformations of uv, as summarized below. Note that any of the following uv-expressions may be suffixed with a or d, depending on whether the signal is in analog or digital form. Note also that a corresponding w can be computed for any of these functions. Note also that these expressions may be affixed to expressions for the points in scene-space to which they relate.

SIGNAL	MEANING	COMPONENTS
Auv	Absolute u or v; a unique facet-point on a figure or in a scene, expressed as two-dimensional coordinates (two dimensions free, one dependent) on a flat array of equilateral triangles	Au, Av, each an integer denoting corridor number and a decimal fraction denoting facet-point

uv	uv in any form	u, v
⁄⁄	uv with coordinates inpointing (when important to distinguish from other coordinate-sets such as Auv)	⁄, ⁄, each a decimal fraction; mapped on the triangle with 0s at apices and 1s at edge midpoints.
Buv	Braided uv	Bu, Bv; consisting respectively of u1, u2 and v1, v2
Duv	Difference in uv (from previous state)	Du, Dv
Tuv	Twirled uv (uv modulated in a spiralling pattern)	Tu, Tv
Cuv	Converted uv (reproportioned in absolute size-units according to actual dimensions of spatial facet in scene-space)	Cu, Cv
Luv	Localized uv (Cuv positioned in actual scene-space: the measured position of uv on a spatial polyhedron)	Lu, Lv

In this embodiment of the invention, the principal work is performed in an array of coordinated units. The lowermost level is an array of holding or representation units, holding data and control information in digital form; the next level converts some of this information to analog form, and passes other parts of it on in digital form; and the uppermost level is composed of surface computing devices.

These arrays are composed of physically separated units which plug into one another, as may be seen in FIG. 12. The digital holding register unit or "hex" HX is hexagonal in shape, the digital-to-analog conversion unit or "bowtie" BT is shaped like a bow tie, and the surface unit or tricell TC is triangular. When massed in planes with their fellows these units constitute respectively the "holding register array" (HRA), conversion unit array (CUA) and surface unit array (SUA). In FIG. 12 we see an array of five hex holding units HX, one bow-tie digital-to-analog unit BT and its seat on the hexes BTS; an upper and lower tricell analog surface computer Utc and Ltc, and their seats on the bow-tie US and LS.

The analog information is distributed by the bowtie to its output pins in a rather complicated pattern as depicted in FIG. 12.

The surface computing cell for each facet requires in practice the lengths of three edges and the unit normals of three influence planes. As these are required by two adjacent facets, they are shared between the two. The exact arrangement has been contrived to supply the surface computation unit, or tricell, with the information required in its surface computations. A curious method

of intercourse for the shared quantities has been devised, affecting the geometry of the design in this embodiment as depicted in FIG. 12. The intercourse of information is depicted in FIG. 20. The upper-facet portion of the bowtie holds If1, Lg2 and If3, which it uses in its own calculations and passes to its neighbors. Its tricell receives in turn Lg1, If2 and Lg3 from its neighbors, where they have been computed and where they are considered to be Lg4, If5 and Lg6 respectively. Similarly, the lower-facet portion of the bowtie holds Lg4, If5 and Lg6, which it uses in its own calculations and passes to its neighbors. Its tricell receives in turn If4, Lg5 and If6 from its neighbors, where they have been computed and where they are considered to be If1, Lg2 and If3 respectively.

The digital unit, or hex, best seen in FIG. 13, fits in a socket with various electrical connections. It fits among others like it, and communicates with them optically through a number of windows and sensors.

In addition to its gross physical features, to be described below, it has a number of electronic subsystems which will be discussed in various places, particularly the registers, command system, immediate aperture-shift system, partition system, and shift system. Its gross features, as visible in FIG. 13, are two power prongs PP on its top, which supply power to the units above it, and columns of spots on its sides HL, HS. The spots on its sides are lights or hex lights HL, and corresponding sensors for the lights of its neighbors, hex sensors HS. These lights and sensors

connect to electronic circuitry within. Columns of six round HL spots are the output lights for the immediate aperture-shift (IAS) system IASL, while columns of six round HS spots IASS are the sensors for receiving IAS signals from the neighbors. A square HL spot BPL (border protect light) is the non-border light, and a square HS spot BPS (border protect sensor) is the border sensor. A round normal shift light NSL is received by normal shift sensors NSS.

The hex unit has eleven pins which insert in a socket in a mounting board, not shown. On the other side of the mounting board is an array of wires running in three directions (directions R, S and T in FIG. 14). Each pin terminates on the other side of a mounting board with eleven wire-wrap pins. Each pin is a single or multiple terminal which is attached to a wire or wires which continues on to connect to other hex units. These lines are the power lines 9, providing input power in a positive and negative multiline, hex command line 10, hex out line 11, shift trigger line 12, shift timing line 13, IAS multiline 14, jumper R 15, jumper T 16, hex select 1 17, hex select 2 18, jumper S 19.

Atop the hex is a gridwork of squares of an electrophosphorescent material, as seen in FIG. 15. Each such small electrophosphorescent square is electrically wired to a binary memory cell (flip-flop) within the hex cell, lighting up if that cell contains a "1". When the hex is loaded, these grids contain information for use in the surface generation system, particularly the coordinates of the headpoint HP, the partition bit PB, surface contour data DT, logic LG and upper localizing matrix ULM and lower localizing matrix LLM. These go to bowtie BT and upper and lower tricells Utc and Ltc as seen in FIG. 12.

Each hex contains a number of digital storage registers, holding the data required for the functioning of the cell and its associated and surrounding tricells.

These registers consist of binary storage units (flip-flops) connected in various ways to each other, to the optical communication panel upward and consequently to the tricells above. The contents of these registers are supplied by the main computer, unless stated to be automatically generated within a hex.

Most of these data may be shifted to adjacent cells when dictated by circumstance. Rather than furnish wiring diagrams or schematics, operational descriptions of the circuitry constituting a full enough specification for their creation by a skilled practitioner will be given later.

Several registers are associated with basic switch logic and cell selection. They are:

DAB, the disable bit. One-bit register associated with tricell. One for each facet. Shows to top of hex. (Automatically generated within hex.)

AP, the aperture bit. One-bit register associated with whole hex. One per hex. Shows to top of hex.

REC, the recognizer register. Four-bit register associated with tricell. Two per hex. Shows to top of hex.

Several registers are associated with the logic of surface generation (as distinct from the registers holding data for surface generation, which will be discussed later). They are:

MEX, the mesh exception registers. Four-bit register associated with facet edges. Three for each tricell.

MXF, the mesh exception flag. Indicates mesh exception, triggering tricell alarm. One for each tricell.

Shows to top of hex.

CIN, the curvature-inactive bit. One-bit register associated with tricell. Two per hex. Shows to top of hex. (Automatically generated within hex.)

BOR, the border bit, a one-bit register associated with a hex. One for each hex. Shows to top of hex. (Automatically generated within hex.)

A unique register constitutes the partition system:

PTN, the partition bit, a one-bit register associated with a hex. Shows to top of hex.

One register is associated with the braider system. This is:

BCH, the braider choice register. Two-bit register associated with tricell. One for each tricell. Shows to top of hex.

Several registers are associated with the shift system. These are:

PDN, the putdown bit. One-bit register associated with hex. One for each hex.

PKP, the pickup bit. One-bit register associated with each hex. One for each hex.

ITP, the IAS triggerpoint bit. One-bit register associated with hex. One for each hex.

Several additional registers, one bit each with one exception, are associated with the shift system. These are always loaded together in one operation as a single register, which we call the prep-word or shift control register PRP, associated with one hex. There is one for each hex. However, the individual parts of PRP

have independent names and functions. They are:

SPR, the shift-prepare bit.

SDM, the shift dimension register (2 bits).

SDR, the shift direction bit.

RAP, the ready aperture bit.

RDW, the ready data word bit.

RCL, the ready cell logic bit.

RPL, the ready partition logic bit.

Several registers hold data for the task of surface generation. They are:

RFP, the reference point location registers, which hold the 3-space coordinates of each reference point. Show to top of hex. In each hex the reference point is the headpoint for an individual bowtie, equivalent to point @. One for each hex.

The hex has in addition the data registers required to specify the curvature of its upper and lower facets, some of which contribute also to the curvatures of Up1, Up2, Up3, Lo4, Lo5 and Lo6.

For the upper facet these registers hold, in digital form, the vectors and quantities necessary for surface generation, as will be fully specified under "tricell operation." These are NmUp, If1, Lg2, If3, Ds@2, Ds@a3, Ds@b1, ULM, NmLo, Lg4, If5, Lg6, Ds@5, Ds@d6, Ds@e4 and LLM. The means by which their data is transmitted to the bowtie and tricell is discussed later.

The hex has a facility for receiving and decoding a number of different commands sent serially from the main computer on the command line (10 in FIG. 14). All begin with a 1, indicating the start of a command, as a 0 would not be sensed.

The commands to the hex are as follows:

1000	No more shifts
1110	Set pickup
1111	Set putdown
1100	Remove pickup
1101	Remove putdown
1011	Set IAS trigger to this cell of dimension T
1010	Remove IAS trigger

The holding system of the hex consists of the digital registers already enumerated.

The presentation system of the hex provides a means whereby the information stored in the holding system may be transmitted to its places of use.

The upper side of each hex is inset with optical output registers, as will be seen in FIG. 15. These are connected to specific registers within the hex and report the contents of these registers to corresponding input registers on the bowtie, as will best be seen in FIG. 16. Since the optical output registers on the hex are matched perfectly to the input registers on the bowtie, we shall consider the data passed between them rather than specify the exact arrangement of these registers.

The bowtie receives optically from the hex, and converts to analog form, the upper-facet quantities NmUp, If1, Lg2, If3, Ds@2, Ds@a3, Ds@b1, and the lower-facet quantities NmLo, Lg4, If5, Lg6, Ds@5, Ds@d6, and Ds@e4. These appear at the data output window array of the hex, as shown in FIG. 15, DT. The corresponding windows on the bottom of the bowtie, wherein these signals are received, are shown in FIG. 16, DT. All these are transmitted to the tricell by means of electrical contacts (not shown), except for quantities If1, Lg2, If3, Lg4, If5 and Lg6, which are transmitted to the cells above through the bowtie's output multiposts in the pattern shown in FIG. 20.

The bowtie receives in addition the upper localizing matrix and lower localizing matrix, as will be seen in FIGS. 15 and 16, ULM and LLM.

The bowtie receives in addition, in digital form, the coordinates of the hex's reference point @, visible in FIGS. 15 and 16 HP, which are converted to analog form and shunted to the @-post (seen in FIG. 12, P1, and FIG. 18, 22).

The bowtie receives, in addition, a partition bit (shown in FIGS. 15 and 16, PB), indicating whether the reference point lies on a partition. This bit is converted by the bowtie from optical to electrical form, and transmitted to the uppermost band of the @-post, shown in FIG. 18, from which it may be sensed by the six surrounding tricells.

The bowtie receives in addition certain digital logic bits and fields, as may be seen in FIGS. 15 and 16, LG; specifically these are disable bit DAB, recognizer setting REC, braider choice setting

BCH, and mesh exception flag MXF. These are amplified by the bowtie and passed on in similar form to the tricells by output windows on top of the bowtie, not shown, communicating with input windows on the bowtie, not shown.

The bowtie receives, in addition, the hex's partition bit, which it distributes through the @-post to the six surrounding tricells.

The partition system provides a means for dividing an array into parts which may be used separately, or used conjointly in compound processes.

Three one-bit registers are associated with the partition facility. Two are in the hex and one is in the tricell.

A partition bit PTN specifies that a hex is part of a partition (if PTN = 1), and shifts into the hex will not be shifted out the other side, nor will IAS pulses be retransmitted by it. (However, shifts into it will be shifted out of a pickup, if one is attached to that cell.)

When such partition bits are set to 1 in a wall of hexes containing connected reference points completely cutting off one area of hexes and tricells from another, the areas so distinctly separated are then called "chambers" or "windows." A separate braider and other controls may be attached to each chamber, and its subarrays will perform like completely separate arrays. (The exact logic by which partition bits affect the cell, are created and shifted, will be discussed in connection with the description and operation of the shift system and the operation of the partition system.)

An adjacent-partition bit AJP exists in the tricell; it is automatically set to 1 if an adjacent hex contains a partition bit, which is signalled through the @-post to surrounding tricells. This adjacent-partition bit is not an ordinary flip-flop but a gated response of each tricell, and automatically shuts off if all hexes around it cease to have their partition bits set.

The partition-shiftable bit PTS in the shift-prep register of

the hex causes the partition bit (whether 1 or 0) to be shifted as a specific field during a shift. This means that if PTS used, partitions will be moved as well as data during the prearranged shift, across as many cells as the shift may require.

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The jumper mechanism provides an input-output facility for the hex. Jumpers provide pathways for shifts, whose terminal points are either "pickups" or "putdowns." A jumper is a line between hexes, or between hexes and the computer, which permits the shifting of information into or between parts of the array. A connection from a jumper into a hex is called a "putdown;" a connection out of a hex is called a "pickup." Putdowns and pickups are technically 1-bit permission registers which are set within the hex, but for convenience we refer to them as though they were concrete objects placed in position there. An input path from the main computer to a hex is created by placing a putdown there; an output path to the main computer from a hex is created by placing a pickup there. Information may then be shifted into the hex (if a putdown) or out of the hex (if a pickup) along jumper lines R, S and T (15, 19, 16 in FIG. 14).

To permit changing the contents of the hex holding units, a shift system has been provided. All change of the contents of the hex holding unit is by means of shifting, including the initial loading of the array.

The shift facility permits the different forms of data to be moved in and out of the holding cells. It provides an input-output capability for transference of data from the main computer, to the main computer, and among parts of the array. Normal shifts, as distinct from IAS shifts, occur between adjacent cells, which become connected into long shift registers by means of the shift commands.

The normal shift subsystem is externally manifest on the hex as two spots on each of the six faces, visible in FIG. 13 NSL, NSS. The normal shift light NSL is the exit for the shifting out of the hex of patterns of bits between cells. The normal shift sensor NSS is the entrance for patterns of bits shifted between cells. The beginnings and ends of shift lines in the array are defined by putdowns and pickups, described elsewhere. The rest of the normal shift system consists of the PRP register and its associated circuitry.

¶ The normal shift system is controlled by several external agencies and an internal register. The external agencies are the hex command line, jumper lines R, S and T, the shift trigger, and the shift timing line. The internal register is PRP, the prep-word register.

The hex command line specifies the creation of putdowns and pickups. By programmed transfer from the main computer, prep-words then enter the cells from the putdowns and are propagated in a direction and modes specified by the contents of the prep-

word. The prep-word remains in the PRP of each hex through which it passes, cocking the cell for a series of shifts having characteristics also specified in the prep-word. Impulses on the shift trigger line now cause the shift for which the cells have been prepared. Synchronized inputs to putdowns from the main computer or other chambers will also participate in the shift.

The shift-prepare or prep-word register, which will be referred to collectively as PRP, is composed of a number of individual short registers which we will name for convenience. Each controls an aspect of a shift. The registers are:

SPR, the shift-prepare bit (1 bit).

SDM, the shift dimension register (2 bits): 01 = R, 10 = S, 11 = T.

SDR, the shift direction register (1 bit): 1 = + (a, b, c), 0 = - (d, e, f).

RAP, the ready aperture register (1 bit).

RDW, the ready data word register (1 bit).

RCL, the ready cell logic register (1 bit).

RPB, the ready partition bit register (1 bit).

The aperture system is a means for restricting possible response by array tricells. The code braid recognizer system being sufficient to distinguish only from among a total of 32 tricells in all, a further method is required to restrict output to only one tricell in larger arrays. The Immediate aperture system (IAS) creates an "aperture" of several tricells in the array which are prepared to respond, and forbids the others to respond. As a uv probe moves from tricell to tricell, the aperture moves about the array to continue surrounding the probe.

As will be seen in FIG. 21, the standard aperture pattern consists of three hexes in a triangle whose aperture bits are "on" or receptive r, rendering sensitive s an array of thirteen tricells in a pattern forming an equilateral triangle with truncated corners. This pattern must be loaded by the computer as part of the process of loading an array.

The aperture system implementing this structure consists of several elements: aperture register, aperture shift line, and aperture shift lights and sensors. The aperture shift lights may be seen in FIG. 13 IASL, as may the sensors IASS.

The one-bit "aperture register" (AP) in the hex determines whether the tricells around it are prepared to respond to a probe, being transmitted to the uppermost band of the @-post of the bowtie (FIG. 12, P1, and FIG. 18, 22), which shows this register to the six surrounding tri cells. If this bit is a one, the tricell can respond; if this bit is a zero it cannot.

The IAS bits have unique shiftability status.

There are six aperture shift circuits, a, b, c, d, e and f,

each controlling an aperture shift in one of directions a-f as shown in FIG. 4. Each is a conducting plane or ring receiving pulses from its aperture sensor (FIG. 11, IASS a-f), amplifying it, and passing it out through all IAS lights having the same direction letter code IASL a-f. Each aperture shift circuit is triggered by an "IAS pulse" having the same direction letter code a-f, corresponding to the six mesh directions as seen in FIG. 4. IAS pulses a-f may arrive either through the IAS multiline in the base of the hex as seen in FIG. 14 14, or by means of a pulse of light emitted by an aperture shift light as shown in FIG. 11, IASL a-f.

The digital-to-analog unit, or bowtie, fits upon the hex unit as illustrated in FIG. 12. The power prongs PP of the hex cell furnish it with power and continue on through it.

Each bowtie has posts P1-P7 by which signals are transmitted upward to its tricells, in a pattern interlocking with posts on adjacent bowties. To provide for the insertion and removal of bowties, each bowtie is grooved so as to slide past the posts of adjoining bow-ties.

Although the posts are arranged with identical irregularity on the bowties, the posts of adjoining bowties, when fitted in place, make a completely regular triangular pattern, with two posts on each side of a triangle and one post at each corner.

It will be seen that the posts of one bowtie exactly complement those of another, so that each tricell will fit into a nest of two vertical posts on a side and one on each corner.

On the lower side of the bowtie, as may be seen in FIG. 16, are gridwork patterns of photosensitive material, arranged in input registers exactly corresponding to the pattern of registers on the top of the hex units. Connected to these the bow-tie contains internally a number of digital-to-analog converters (DACs) which change the contents of the digital data words in the hex units to analog voltages proportionate to the magnitude and sign of the numbers held in the digital registers of the hex unit directly beneath it, which is the only hex unit which gives it information. The logic bits from the hex below are in most cases passed through unchanged to the far side of the bowtie, exiting through another electrophosphorescent output register (not shown) and

similarly received in the tricell.

Since all aspects of such transformations are well known, no further description of the bow-tie's internal mechanism is necessary here.

The voltages from the DACs are then brought up to the top of the unit, where they appear at successive sleeves of contact posts there. These posts are divided into successive metal contact sleeves as will be seen in FIG. 17, mating with a divided shoe on the tricell, so that the several different quantities required to specify a certain element all appear at the same pin. All posts have three contact areas except the post representing the head-point, which has five, as will be seen in FIG. 18, 22. These five contact areas carry analog signals representing xyz@ and digital signals corresponding to registers PTN and AP.

The uppermost unit, or tricell, TC in FIG. 12, is a hybrid computer triangular in shape and mechanically fitting within one triangular seat on a bowtie and surrounded by contact posts, which it is grooved to fit. It has contact plates in each groove for receiving the separate voltages from the bowties beneath it, as shown in FIG. 17, 21. The tricell also has sockets beneath it (not shown) for the power bars coming up from below, and contacts and multicontacts on its top (MC in FIG. 12) to receive certain query signals and send out its answers and other signals.

The tricell receives from the hex unchanged, in digital form and unmodified by the bowtie, the contents of registers DAB, AP, REC, MXF, CIN, BOR, PTN and BCH. These parameters are viewed by photoelectric receptors linked to logic circuitry within the tricell. In addition it receives at its corners the digital partition bits of the three reference-point posts which it touches, and their aperture bits.

In analog form it receives three reference-point locations from the surrounding reference-point posts. In addition, it receives from its bowtie and surrounding side-posts its own unit normal vector, three influence vectors, three lengths, three distances and a localizing matrix. If it is an upper tricell these quantities are NmUp, If1, If2, If3, Lg1, Lg2, Lg3, Ds@2, Ds@a3, Ds@b1, and ULM. If it is a lower tricell these quantities are NmLo, If4, If5, If6, Lg4, Lg5, Lg6, Ds@d5, Ds@d6, Ds@e4, and LLM.

In addition to the logic and data registers presented to the tricell via the bowtie, the tricell may be considered to have three "registers" of its own, i.e., modifiable digital settings, even though these are not true flip-flop registers as in the hex.

These are:

ON, the on bit, a one-bit register which turns on when an excursion is inside that cell. It is transmitted out through one of the tricell's external contacts (31 in FIG. 19).

AJP, the adjacent partition bit, a one-bit register which indicates that a partition is at one of the three corner reference point locations of that tricell.

ULS, the upper/lower select register, specifying whether the excursion is presently in an upper or lower cell.

As the exact operations to be performed within the tricell will be detailed under "operation," a functional description of its activities is given here as part of the description.

The tricell is internally wired as a hybrid computing mechanism so as to use the data and logical information thus brought to it for the generation of surface-points in scene-space when called to do so as a selected member of an array, recognizing an enabling combination of braider setting and aperture by means of a recognizer and switch logic, unbraiding Buva to uva, switching off if the signal calls for a lower cell when it is upper or vice versa, converting uva to uvwa and uvwa to Cuvwa and Cuvwa to Luvwa and deriving from Luvwa xyz and tp.

A number of multiterminals are wired in parallel between tricells as will be seen from FIG. 19. Input terminals at the top of the tricell are as follows: uva 23, provided for testing and maintenanace; and Braiders B1 24, B2 25, B3 26, selected by braider choice register BCH within the hex registers and 1-volt reference 1v.

Output terminals at the top of the tricell are xyza 27, tpa 28, hit 29, alarm 30 and ON 31.

A number of devices may be connected to the array to control or aid in its function. These "array control devices," as we may call them, will now be described. They are, specifically, the view calculator, braider, twirler, Pythagorean distance unit, edge-checker, homing unit, reflector, edgetracer, slicer, aperture control and irregularity control.

The view calculator, whose inputs and outputs are illustrated schematically in FIG. 24, is a device which may be presented with analog signals (voltages) x, y, z representing by their magnitude the coordinate position of a point in three-dimensional space, and which will return for each such set of signals a pair of voltages p,q which represent the position of that point in a picture seen from a digitally preset vantage point L.

In the uses here it will make such evaluations with respect both to the vantage point of the hypothetical camera (always designated L for "lookout" as in FIG. 33) and to one or more light-points (designated L1, L2... and likewise to be seen in FIG. 33), in order to ascertain facts about visibility and shadow in a scene.

Since many such pieces of equipment are commercially available (the "Scenoscope" of optical Electronics, Inc.; the Adage AGT/50 Graphics Terminal; the LDS-1 display of the Evans and Sutherland Computer Co.; the view display of Vector General, Inc.; and the architectural-drafting machine of Perspective, Inc. are examples), this equipment needs no discussion here.

The braider is a device which creates a set of coded control voltages for the exploration of a surface represented in the array or a chamber thereof. It constitutes also an input-output device with which the computer may "point to" a facet or facet-point requiring examination.

The basic mechanism is a calculation network which electrically converts the varions inputs to variations in the code braid (FIG. 10, explained elsewhere).

Functionally described, the braider is a mechanism which produces the uv control signals in their compound coded form, Buv, which selects among cells. The mechanism operates from digital and/or analog inputs, sends out signal pulses when the code braid passes cell boundaries, and maintains tallies of these boundary crossings.

A diagram of braider BR may be seen in FIG. 25. It has a number of input lines and multilines, including those for its control by Dua s8, Dud s9, an external Du amplifying signal s10, Dva s11, Dvd s12, an external Du amplifying signal s13, va s14, vd s15, ua s16, ud s17, and start and stop control signal lines s6, s7, reset control line s29, and command line s30. Its outputs are Buva in either analog s18 or digital s19, together with a u tally pulse line s27 and a v tally pulse line s28. u and v counts at all times appear at outputs s31 and s32.

The braider's principal subunits, in addition to various digital registers DR and DMAC conversion units, are Du mixer 51, Du tweak amplifier 52, Dv mixer 53, Dv tweak amplifier 54, Bu calculator 55, Bv calculator 56 and 45° phase interlock control 57 between them. Two other subunits of interest are recognizer and

converter 58, which recognizes Buv crossings and tallies them, holding them in digital registers for release on lines s27 and s28 respectively, and braider control 59, which effectuates start and stop pulses arriving on lines s6, s7. BR has output lines for the code braid Buv in analog s18 and digital s19, as well as for separate u- and v-crossing tallies s27, s28 and digital counts of the present u and v corridors s31, s32.

The twirler provides an exploratory steering pattern which is fed to the braider to perform explorations on a surface represented in the array.

A diagram of twirler TW may be seen in FIG. 26. The unit has inputs for halt signals s36, "volume control" of twirler intensity s37, and a "tweak amplifier" temporarily enlarging its excursions s38. Its outputs are twirled u Tua s41 and twirled v Tva s42. Its significant subunits are sine-wave oscillator 61 for Tua and sine-wave oscillator 62 for Tva, the two being held by phase interlock control 63 to 90° out of phase, amplifiers 64 and 66, and tweak amplifiers 65 and 67.

The Pythagorean distance unit (PDU) has its inputs and output schematically illustrated in FIG. 27. Inputs xyz1 and xyz2 enter the unit in either analog or digital form. If in analog form, they enter on lines s45 and s47 respectively; if in digital, lines s46 and s48 respectively. The distance Ds between the two entities exits the PDU on multiline s49. As long as there is any distance between xyz1 and xyz2, a signal is present on miss-line s51; when the two points fuse or are identical, signal s51 ends and a signal appears at hit-line s50.

The inputs may also be two-element vectors such as pq, in which case the result at s49 will be the distance between the elements in two dimensions.

Edge checker EC, whose external signal contacts are illustrated in FIG. 28, tests whether the tangent plane tp at hitpoint xyz goes through vantage point L, which means that xyz is on an edge relative to L.

EC has input multilines s56 for the tangent plane signal in question, s57 for the coordinates of the L of the viewpoint being considered, xyzLd, which is held in a DR and thence converted to analog in a DMAC, and s58 for the current hit-point signal. It has output lines s59 for a hit signal and s60 for a miss signal.

The homing unit progressively brings a probe excursion closer to a specified point on a picture-projection of the scene as monitored by a view calculator and Pythagorean distance unit. When xyz has been driven to coincidence with the sought point pq, an output signal so informs the computer.

A diagram of homing unit HU and its relation to the array as its environment system may be seen in FIG. 29. There is/an array system of twirler 170, braider 171, surface unit array 173 attached by means of transfer units (bowties) 175 to holding register array 174, and an edge checker 172 attached to surface unit array 173, which is also attached to view calculator 176, and a Pythagorean distance unit 177 attached to view calculator 176. All of these devices save HRA 174 are attached to homing unit HU.

The homing unit HU contains two significant subunits in addition to an ADC, a DAC, DRs, DMACs and MADCs. These significant subunits are differential analyzer 179, which emits a pulse when its input begins to increase, and delay line timer 178 whose digital delay is 2/3 of the twirler cycle.

Output lines of the HU include a strobe s76, s77 from delay line timer 178 to the tweak amplifier, a control signal s78 from the differential amplifier to the volume control of the twirler. TW also receives difference signals from PDU 177, as passed s74 to various subsystems of HU. Outputs of HU are Buva, xyz and pq, which are available in analog s81, s83, s85 and digital s82, s84, s86 forms respectively.

Input lines include Buv s70 from braider 171, xyz s71 from surface array 173, and pq from view calculator s72.

The reflector RFL is a device for calculating a signal representing a reflected ray from a surface point xyz relative to a lookout or light LN. In the present embodiment it is based upon the arriving angle of the ray, the hit-point on the surface xyz, and the tangent plane of the hitpoint tp. A schematic drawing representing the inputs and outputs of this unit will be seen in FIG. 30.

RFL operates by vector operations involving representations of two points in space, xyz1 and xyz2, representing endpoints of the arriving ray, the latter being the hitpoint, and the tangent perpendicular tp at hitpoint xyz2. These arrive at RFL on lines s90, s91 and s92 respectively. The solution ray, a 3-part vector constituting the unit vector of the desired reflection, exits RFL on line s92. The internal mechanism will be operationally described in terms of its calculations under "operation."

The edge tracer is a device for exploring the relative edge of a surface as seen from vantage point LN by controlling the motion of an excursion upon it. It accomplishes this by feedback principles, controlling the movement of the probe on the represented surface in a circular scanning pattern supplied by the twirler. At each instant the probe touches or crosses an edge relative to LN, the probe's coordinates uv and xyz are recorded. After two crossings, the distances from the starting point are compared and that more distant is selected as a new starting point. Its coordinates uv and xyz are taken as edge coordinates and passed on.

A diagram of edgetracer ET and its relation to the array system may be seen in FIG. 31. An array system of twirler 101, braider 102, surface unit array 104 attached by means of transfer units 105 to holding register array 106, an edge checker 103 attached to surface unit array 104, and view calculator 107, are collectively attached (with the exception of HRA 106, which is attached only to SUA) to edgetracer ET. Also attached to edgetracer ET are two Pythagorean distance units 108, 109.

The edgetracer ET contains a number of significant subunits in addition to various MADC and DMAC conversion units. These significant subunits are: three devices which shall be called "coholders," being units which hold simultaneously two or more values for comparison and subsequent transmittal, specifically uv coholder 110, xyz coholder 112, and pq coholder 113, each of which receives its apportioned quantities from generating units in the array: respectively uv from braider 102 on line s202 and s209, xyz from surface array 104 on line s205 and s210, and pq from view

calculator 107 on line s206 and s211; a coholder control 111 attached to edge checker 113 by line s203; and a comparator 114 attached to the coholders 110, 112, 113, to twirler 101, and to Pythagorean distance units 108, 109. The edgetracer ET also contains various digital registers 93, 94, 95 used for buffering output.

The slicer SL is a device for calculating the boundaries of an object's intersection with a slicing plane. It traces "slices" around the perimeter of an object, controlling the motion of an excursion on the intersection of a given plane with a surface. This may be used for scanning the object for a regular array of picture-points, or a raster array of picture-points suitable for television; or it may be used for contour maping and other purposes.

Slicer SL, seen schematically in FIG. 32, operates by an analysis of the p and q outputs of a view calculator VC, watching a view of the object from a slicing lookout or light LN. A q-watching unit or q-checker 135 determines when the probe is on the slicing-line, and a p-watching or p-control unit 134 determines when an excursion-point is farther along the slicing line than before. Analysis of the tangent perpendicular by flipper 131 indicates whether "farther along" is in the positive or negative direction of p. At each instant the probe crosses the slicing plane, the probe's coordinates uv and xyz are recorded. Those coordinates which form an appropriate continuation of the slicing record are passed on to output.

The slicer view calculator 126 has its view coordinates rotated so that dimension P is to be the direction of slicing, a horizontal line of a view from LM; a slice on the object will be along a p coordinate of the view calculated by VC(LM). An additional view calculator 128 provides a view of the slicing and contours as seen from LN.

A diagram of slicer SL and its relation to the array system may be seen in FIG. 32. There is an array system of twirler 120, braider 121, surface unit array 123 attached by means of transfer units 124 to holding register array 125, and to edge checker 122

attached to surface unit array 104, which is also attached to two view calculators 126, 128. All of these devices save HRA 125 are attached to slicer SL.

The slicer SL contains a number of significant subunits in addition to various ADC, DMAC and MDAC conversion units. These significant subunits are starter 129 attached externally to twirler 120, flipper or sign-reversing unit 131 attached to edge checker 122, digital uv holding register 130 attached to braider 121, digital xyz holding register 132 attached to the surface unit array 124, p-control unit 134 composed of p-compare unit 134a and p-coholder 134b with p-holding registers 134c and 134d attached to view calculator 126, q-control 135 containing q-registers 135a and 135b attached to view calculator 126, and q-holder 133 attached to q-control 135. The slicer SL contains also various digital registers 136, 137, 138, 139 used for buffering output.

The aperture control (APC) is required to change the boundary-crossing tally pulses supplied by the braider into IAS pulses which drive the movement of the aperture. This is due to the unusual geometry of the system. The movement of the probing aperture (seen in FIG. 21) is in mesh dimensions R, S and T, while it is responding to movements in dimensions u, v and w which are 30° out of line with R, S and T. The aperture control compensates for this.

The APC consists of analysis circuitry and a register composed of two flipflops, the IAS control register (not shown). This device is connected to the outputs of the braider and feeds the IAS system through the IAS lines at the bottoms of the hexes.

The irregularity control (IRC), not shown, is a device which operates in conjunction with the array. Its inputs are connected to the tricell alarm lines (30 in FIG. 19) and the hex-out lines (11 in FIG. 14). Its output system is connected to the interrupt system of the main computer. The IRC examines irregular responses by the array, as signalled by cell alarms, and takes appropriate action.

Besides separate mechanical and electronic devices, this system requires the use of a number of unusual lists for its internal functioning.

In this context, a "list" is an arrangement of linked areas in computer storage with corresponding parts for the storage of corresponding information. (The term "table" is often used for this type of list.) This list means may be transformed into various other forms than those described here, all within the scope of this invention.

The mesh table specifies the mesh connections among reference points in the surface data.

The mesh table takes the following form in digital storage:

MESH TABLE (independent of LN)

Ref. Point no.	R,S,T position	Coordinates x	y	z	Connected points a	b	c	d	e	f	Facet Nos. of Upper & Lower Facet

The facet table contains data giving the headpoint of each facet for reference, and showing the spatial location of the center of each facet, and the greatest curve or bulge expected from that facet.

The arrangement of the facet table in digital storage is as follows:

FACET TABLE

Facet no.	Headpoint no.	Lower or Upper?	Center Loc.	Expected Max. Bulge

The data web table gives the data necessary for curve generation.

In digital storage its format is the following:

DATA WEB TABLE

(converted by computer from other tables)

Ref. Point no.	Location	Upper Facet no.	Upper Facet Data	ULM	Lower Facet no.	Lower Facet Data	LLM

(The upper facet data for the present embodiment are, as has already been explained, NmUp, If1, Lg2, If3, Ds@2, Ds@a3, Ds@b1. The lower facet data for the present embodiment are, as has already been explained, NmLo, Lg4, If5, Lg6, Ds@5, Ds@d6, and Ds@e4.)

The view table for LN contains data about the points and facets as seen from LN; it varies depending on the LN from which it is taken. It is of use in determining what facets obstruct what other facets from a particular point of view.

VIEW TABLE

Ref. Point no.	Distance from LN	pq	UPPER FACET		LOWER FACET	
			Center Dist. from LN	Enclosed Centerpoints	Center Dist. from LN	Enclosed Centerpoints

The mantle is the system of invisible surfaces radiating outward from a vantage or light LN and defining the visibility or occultation of surfaces with which they intersect by dividing these surfaces into areas which are visible and invisible, shadowed or unshadowed.

In the present implementation we approximate the mantle by a representation of its constituent edges on near and far surfaces, and points on those edges, called events, which may be used to locate corresponding places on the other surface or in a scene. In the case of a light LN-except-L, the near edge is what casts a shadow and the far edge is the edge of that shadow. In the case of a vantage L, the near edge is the visible edge of the near object, the far edge is the line on the far object traced with respect to L by the near edge.

The edges with respect to LN we call near and far edges.

The mantle list takes the following form in digital storage:

MANTLE LIST

(sorted in order of ascending event-distance from LN)

EVENT NO.	EVENT CODE	EVENT NO. OF MATE (CORRESP. U or L EVENT)	FACET NOS. (2 IF ON BOUNDARY)	uvd	xyzd	Dist. from LN	Neighboring Events on Edge: Previous	Neighboring Events on Edge: Next	Edge no. in Mantle

Event codes for the table are as follows:

000	Fold (fusion of upper and lower edges) (requires two adjacent event nos., one for each edge)
001	Drop-point to a jut
010	Emergence-point on a jut
011	Catch-point below a jut
100	Near coordinates of near boundary crossing (requires 2 facet nos.)
110	Far coordinates of near boundary crossing
101	Near coordinates of far boundary crossing
111	Far coordinates of far boundary crossing (requires 2 facet nos.)

The encounter list has several different functions. It serves in the allocation of chambers, array controls and output. It tells various parts of the system presently embodying this invention what curves are encountered in a succession of left-to-right sweeps progressing downward through the picture area, as seen from L. It is of use both for scanned picture-making and other purposes.

The encounter list resembles the product of two or more mantles M(L), M(L1), etc., as they come to be seen in view coordinates pqL, since it includes the intersection-points of view-edges enL and efL with shadow-edges enL1 and efL1, derived from the L1 mantle (etc.). It lists both the curves to be encountered in the picture and the "nodes," where two or more distinguishable curves of the picture intersect. It contains in addition the intersections of color-edges with the above curves, as well as all upturns and downturns of any of the above curves.

Finally, it is ordered according to the left-to-right occurrence of every curve in successively lower horizontal sweeps.

The encounter list takes the following form in digital storage:

ENCOUNTER LIST

NODE, if any			CURVE (OR CURVES) TOUCHING NODE				New Field		Next Encounter		Remaining		Edginess	
Node no.	pq of node	CTN	Curve no.	Curve type	Curve's Progress	Auvd of Curve	IN	NC	CN	no.	C	N	B	T

The code for curve type is:

00...00	enL
1	enL1
10	efL1
11	enL2
100	efL2
101	enL3
110	efL3
.	
.	
.	
11...11	ec (formula no.)

The code for curve progress is:

First two bits:

01	From above
10	Continuing below

Second two bits:

01	From left
10	On to right

IN here stands for "item nature." The extensible code for item nature is:

1	shadow L1
10	shadow L2
11	shadow L3
.	
.	
.	
N(binary)	shadow L(N)
11...11	color field

CTN here refers to the number of curves touching the node (curves-touching-node). A curve passing through the node, or tangent to it, counts as two curves.

NC here stands for "new color," indicating that the node or curve is the beginning, in the scan, of a new output color field.

CN here refers to the specification, "curve or node?" 0=curve, 1=node.

C here means the number of curves remaining to be encountered in the scan.

N here means the number of nodes remaining to be encountered in the scan.

B here means the point is on a defined "border," to be shown distinctly in output. T is the desired thickness for such a border.

In addition to a surface system, embodied here in the array and its associated devices, an essential component of a half-tone picture computing system is a color system, whereby the colors of the represented surfaces may also be represented. We may represent them either by shades of grey or in terms of the primary colors red, blue and green, which when mixed on color film or color television can produce any color.

The coloration is expressed in a table in core memory, disk memory or other computer memory, in the following form:

COLOR TABLE

facet no. (in ascending order)	flat locus (equation or inequality)	color expression		
		red	blue	green

The points, lines or areas to be colored are specified in some computer representation of a flat locus (uvw representation of flat-points) as a calculable algebraic expression, specifically a set of equations or inequalities, such as $v = u/2$, or $(v<3<u\leqslant 4)$. For each such well-defined locus in the flat coordinates of a specified facet, a set of three calculable color expressions is supplied specifying the relative intensities of red, blue and green. Example: $g = \frac{1}{2}r$, $(u-v)\ r/2 = 7$, $b = 0$. If black-and-white is wanted, only one variable need be specified.

An alternative embodiment of the color lookup system, not illustrated, would use a system of cathode-ray storage tubes having both input and output ports, both being addressable by a random-access point-plotting display control such as the Digital Equipment Corporation 338.

One storage tube is used for each of the primary colored lights, red, blue, and green. The cathode ray tube coordinates x and y are made to correspond to Auva on some portion of the data web.

In a dissimilar embodiment of a surface representation means, the HRA and SUA would be replaced by a subsystem composed of read-write cathode ray storage tubes and associated circuitry. This has the advantage of more easily permitting the use of a more flexible surface function, one with raised arches at its facet edges rather than coincidence of the generated surface with the straight facet edges as in the principal embodiment described in this application.

In this storage tube surface system, the curvature methods to be described do not have the problem of "quilted" surfaces, described elsewhere.

Continuously varying functions for surface generation are stored on storage cathode-ray tubes, and read beams directed to these representations to ascertain the values of the functions for particular corresponding input values.

Physically this embodiment employs one or more cathode-ray storage tubes, such as those available from Tektronix, Inc., having x-y addressability of write beams as an output device from the computer, x-y addressability of read beams as another outputdevice, and sensors from the CRT read beam as input devices indicating the light-dark condition of the screen as it is being read, connected with timing or other circuitry telling the instant (and thus position) of brightness changes sensed on the screen.

Curved lines stored on the storage tube represent the profiles of arches between reference-points in scene-space. Thus three such curves can represent the arch-profiles of sides 1, 2,3 in FIG. 6, or edges on dimensions T, S and R. The x-dimension (of the storage tube) then represents the proportionate length of a curve

and the y-dimension represents the proportionate raising (or lowering) of that curve between two reference points in the scene,

3 proportionate to the curve's height above or below that space edge.

The array and other devices described herein are under the control of a master computer, which guides their actions through an operating system. This general-purpose computer, with its operating system, functions principally as a repository for surface data, a task scheduler, output controller, and interrupt handler. Its functions are described directly or implicitly in this application, and as this cumulative description is sufficient for its creation by skilled practitioners, further specification will be omitted.

Attached to the master computer is a variety of output devices, including x-y plotting oscilloscopes and cameras to photograph them, including still cameras and motion picture cameras. In addition, a video disk unit and videotape recorder, and a special-purpose television raster-switching unit, to be described later, are also interfaced. All these devices, excepting the television raster-switching unit, are interfaced in the conventional manner, whereby the computer may specify individual points in an output picture and the coloration or shading of said individual points.

Operation

Operation of the system must be described at a number of levels: operation of the parts of the array, enumerated as a number of functioning systems and subsystems; operation of the array control devices; overall gross and complex operations of the system, combining and using the operations of the various parts; and complete operations of the system, in which the previously described operations are employed to create picture information which is stored or sent to output devices.

The hex commands are used in conjunction with the hex select lines (17 and 18 in FIG. 14). A signal on both hex select lines 1 and 2 is simultaneously required at a hex for all commands except 1000, which takes effect whenever received.

1000	No more shifts
1110	a pickup is set at this hex, automatically terminating whichever jumper attached to this hex has a putdown elsewhere on its length. A pickup register in the hex, not shown, is engaged.
1111	a putdown is set at this hex, automatically terminating whichever jumper attached to this hex has a pickup elsewhere on its length. A putdown register in the hex, not shown, is engaged.
1100	the pickup register is disengaged.
1101	the putdown register is disengaged.
1011	this cell becomes an IAS triggerpoint for any IAS pulses travelling on its IAS multiline. Sets ITP bit.
1010	this cell ceases to be an IAS triggerpoint. ITP bit is unset.

The holding system consists of the hex registers described earlier. It is loaded by the computer through the shift system. In operation, most of its contents are displayed electrically, as enumerated elsewhere, to the bowtie via the hex windows, and thus passed into the presentation system. Shifting of materials stored in these registers may occur to any of six adjacent hexes, as described in connection with the shift system. Such shifting is under control of the separate fields of the prep-word, as described under shifts.

The operation of the presentation subsystem, following the description given earlier, needs no detailing here, since its mechanism is obvious to any practitioners of the art.

Operation of the jumper system occurs as follows.

Putdowns and pickups are placed and removed by hex commands, described elsewhere.

Commands 1111 and 1110 addressed to a specific hex by the computer through the hex command line directs the hex to attach itself to or detach itself from the jumpers. Logic within the hex underlevel automatically sets or detaches the putdown or pickup, by the setting of PKP or PDN. PKP set "on" means that a shift out of the hex is amplified and sent onto the jumper line. PDN set "on" means that a signal on the jumper line is shifted into the hex. A putdown or a pickup, but not both, may be attached to a particular hex. It may be attached whether or not there is a partition bit in that hex.

In various processes of this invention, simultaneous usage of separate surface representations is required. These separate surface representations may be embraced within a single array by dividing the array into separate or distinct "chambers" as previously explained. Such chambers isolate a probe and restrict shifting operations, preventing shifts within the chamber from proceeding outside the delimited subarray of tricells.

Such chambers, demarcated by partition bits, are created by the computer and its monitoring program, being effected in the array by means of the shift mechanism. A pattern of partition bits is shifted into the array by successive shift commands into jumpers set along different borders of the area to be made into a chamber. These partition bits create a partition or wall between sections of an array.

Partition bits may be left in position while data is shifted, they may be created and shifted independently of data, or they may be shifted in conjunction with data. (The means of so distinguishing is incorporated in the shift system.) This is of use in making chambers smaller or larger while not removing the data they already contain.

A partition will generally be created or destroyed by means of shifting a stream of partition bits lengthwise through the array. However, it may be desirable to change the size of chambers by moving their sides farther apart or closer together; this is accomplished by shifting the partition sideways, along one cell row at a time. Such a sideways movement may occur during the same shifts in which a chamber's contents are altered.

The following rules adequately specify the partition behavior of a cell:

The partition bit prevents shifts out of a cell and invalidates curvature functions in all adjacent tricells. Both data and partition bits can be shifted according to the various shift permission bits in the shift-prep register PRP, as described elsewhere.

When cell contents are being shifted away from a partition, and cells nearest the partition are vacated with no replacement of their contents from a putdown, their data bits are all set to 0. In addition, the curvature-invalid bit CIN is set in them. All shifts out of a hex having no putdown and a non-moving partition are set to 0 except the curvature-invalid bit. In addition, a shift out of a cell containing a data and a curvature-invalid bit of 1 shall have this bit reset to 0 if any bits in the incoming data fields are 1, indicating validation of its curvature function.

The shift system is the principal input and output method used for changing the surface representation data and ancillary information in the hex.

The shift system permits the loading and moving of information in the array. In addition, it allows information to be moved among chambers of the array.

(It should be noted that the computer maintains an accurate tally of shifts in order to ensure that the data is appropriately disposed within the array.)

It is ordinarily unnecessary to alter the braider setting during a shift of both data and cell logic, since the braider continues to address the same set of data.

The initial contents of the hex, including data, partitions and mesh exceptions, are initially loaded from the main computer by shift commands, and most subsequent change in its contents takes place by the same means.

The shift system is also used to transfer information between chambers of a partitioned array with comparatively little attention from the main computer, except to set jumper lines. In this case a pickup is set in one chamber and a putdown in another. The information shifted into one pickup may be simultaneously tapped from putdowns in more than one chamber.

Contents of shiftable registers may be partly shifted to permit a partial change in a chamber's contents without full reloading; the data for many facets may remain in a chamber whose contents have been partially changed.

A shift occurs in two stages. First, a "shift prepare" word or "prep-word" appears at a putdown, to which it has been sent by

the computer. Conditions are changed in the hex units according to the prep-word's contents. Each cell stores the contents of the prep-word as instructions within its own PRP shift control register and immediately passes the same information to its neighbor. In each unit the prep-word is amplified, and its pulses and timing retuned, and sent along to the next unit on the same dimension almost instantaneously unless PTN = 1.

The shift of the prep-word is by this means immediately propagated down a row of hexes, the direction of propagation being determined by the prep-word contents. The prep-word continues shifting by itself through all hexes in the shift direction it specifies until it reaches a pickup, a partition or a border.

Propagations of the prep-word stop, not being reamplified, under the conditions specified in the following table. (Note that if the pickup bit is one, meaning a pickup attachment to that cell, the contents do shift into the pickup but not out the other side of the cell.)

PARTITION BIT	RPB (read partition bit)	PICKUP BIT	SHIFT OUTPUT TO NEXT HEX IN LINE?
0	0	0	YES
0	0	1	NO
0	1	0	YES
0	1	1	NO
1	0	0	NO
1	0	1	NO
1	1	0	YES (incl. shift of partition bits)
1	1	1	NO

At the instant a hex finishes passing along the prep word, it is ready to shift its other contents and receive new contents. However, so that all hexes may shift simultaneously, the main computer specifies the instant of shifting, and waits until sufficient time has elapsed for the prep-word to pass through all hexes. It then sends a pulse through the shift trigger line, which stimulates all prepared hexes to perform the specified shift. The shift is synchronized by pulses on the shift synch line.

This actual shifting is the second stage of the shift cycle.

Contents of the prep-word are as follows:

1. Attack bit. This is always a one; it lodges in SPR, and sets an internal timer in the hex to identify the next bits.

2-3. Dimension, lodging in SDM.

00	No shift
01	Shift R
10	Shift S
11	Shift T

4. Direction on specified dimension, lodging in SDR.

1	+
0	-

5-8 Shift class, determining what parts of a cell's data are to be shifted. Each bit causes the shifting of another class of data, as follows:

Field No.	Register in which it lodges	Contents to be shifted
1	RAP	Aperture bit
2	RDW	Data registers (Nm, If, Lg, Ds, ULM and LLM)
3	RCL	Cell logic
4	RPB	Partition bit

The contents of the prep-word lodge in register PRP. All its subregisters are set by corresponding positions in the prep-word and unset by hex command 1000. The PRP registers whose names begin with S specify shift pathways, viz.:

SPR renders the hex ready for a shift.

SDM specifies the dimension of the shift, disabling the other two dimensions.

SDR specifies the direction of the shift, disabling the alternative.

The PRP registers whose names begin with R specify which hex holding registers are to participate in the impending shift, viz.:

RAP readies the aperture register.

RDW readies the data words (Nm, Lg, If, Ds, and LMs).

RCL readies the other cell logic (CIN, BOR, DAB, REC, BCH, MEX, MXF).

RPB readies the partition bit.

There are four possible information fields that can be shifted, depending on the prep-word. Internal gates and clocking mechanisms in the hex will synchronize the shifting of the right fields in the right order. The four shift fields, in the regular shift sequence, are as follows:

1	2	3	4
Aperture bit	Data Coordinates, etc.	Cell Logic	Partition Bit

Internal logic in the hex examines the prep-word lodged in PRP and gates only the information fields which have been called for in the prep-word. Any fields of information which are not specified in the prep-word are skipped, so that when a field has been completed the next timing pulse automatically specifies a bit in another field which is to be shifted, unless the shift has been completed.

An arrangement of digital circuitry within each hex provides for the automatic timing of all shifts even though the shifts may contain different numbers of bits depending on their internal control registers as set by the prep-word. This is effected by prearranging a fixed count in read-only storage for each shiftable field of a cell's contents; scanning bits 5 to 8 of the prep-word by successive bit positions, and where a one is present, initiating the necessary count (as stored in a read-only field count register within the hex) for the shift of the corresponding data or logic field.

The aperture system operates as follows.

The aperture pattern of three bits in a triangular pattern (as in FIG. 21, r) is initially loaded by the computer as part of the filling of a chamber. Thereafter its movements are controlled by aperture shift commands. An aperture shift is determined by a pulse to an aperture shift line in one hex. This pulse is amplified and communicated by conductor planes within all hexes to all other hexes. An IAS pulse may be received by a hex either through one of six IAS pulse terminals in its base, or through one of six IAS pulse sensors in its side, as seen in FIG. 13, IASS, a-f. Each of six different IAS ports on each side of a hex, called a, b, c, d, e and f, as will be seen in FIG. 13 IASS, causes a hex to shift its aperture bit in direction a, b, c, d, e or f respectively. The aperture shift command need only be given to a single cell within a chamber for it to propagate throughout that chamber. Upon receiving an IAS pulse, a hex sends its aperture bit in the specified direction a-f in FIG. 4 and flashes the same IAS pulse optically to all its neighbors from the corresponding IAS light on all sides, as is seen on one side in FIG. 13, IASL. This assures that regardless of what hex originally receives the IAS pulse, all hexes connected to it within the same chamber will receive the same shortly thereafter in a parallel spasm. (Since the partition bit prevents repropagation of the IAS pulse, the IAS spasm does not leave the chamber to which it is originally directed.)

Once the pulse has occurred in a given hex, it cannot occur again for a set period of time, in order to prevent its accidental repropagation. A delay in the IAS pulse amplifiers of the hex disables the IAS mechanism briefly so that it cannot be pulsed

again in that direction until the pulse propagations have ceased in its region.

The first IAS pulse in a chamber arrives through the IAS multiline in the base of the hex, as shown in FIG. 14 14. Selection of the hex to have this honor is in two stages: selection of a hex by the setting of hex select lines 17, 18, followed by arrival of the "set IAS trigger" command 1011.

This sets the IAS triggerpoint bit ITP, making the particular hex sensitive to IAS shift commands; it remains so until the "remove IAS trigger" command 1010 is seen by the hex. While the ITP bit is set, IAS pulses to IAS line 14 cause an immediate aperture shift by the hex, which stimulates equivalent shifts in all six of its neighbors.

The operation of the bowties requires no further description, that having been incorporated implicitly in the description and operation of the "presentation subsystem," embracing both bowtie and hex.

The operation of the tricell is as follows.

Each tricell is internally coded to respond to a certain combination in the control braid by comparing the incoming voltages to each other and to reference voltages of 0 and +1. This internal debraiding code, called the recognizer setting, may be electrically changed at any time. It is stored in the hex and transmitted up through the bowtie to the tricell, and consists of four bits: two bits for each control variable, u and v.

These recognizer settings of specific tricells are preset by rows within the array, as will be seen in FIG. 11. Each tricell in a row or corridor having the same value of u is given the same Bu setting, as is each tricell in a row having the same value of v. (Lines of equal u and v are demonstrated in FIG. 8).

The recognizer setting is a 4-bit code, composed of a two-bit recognizer setting for Bu and a two-bit recognizer setting for Bv. The logic is as follows. The first bit of the recognizer setting for either control variable determines whether the first or second voltage is to be used, and the second bit determines whether it is to be subtracted from 1. Again we illustrate for Bu.

Range	u formula	u recognizer setting
A	u = u1	10
B	u = 1-u2	01
C	u = 1-u1	11
D	u = u2	10

The complete 4-bit recognizer code of a tricell consists of the two Bu recognition bits fillowed by the two Bv recognition bits.

Let us take an example. In FIG. 11, a schematic drawing of a tricell array, the u and v axes are labelled with the braider ranges to which sections of the array are to respond. Supposing then that

v1 is in range, v2 is past threshold positive, u1 is in range, u2 is past threshold negative, then Bu is in range C and Bv is in range A. Thus only cells 7, 8 in the diagram will respond, although the same four input signals (representing two quantities) are presented to all.

These two cells will, in accordance with their shared corridor position, contain the recognizer settings 1110.

Selection between two cells having a common recognizer setting, such as 7, 8 in FIG. 11, is accomplished by circuitry prohibiting response depending on the sum of final u and final v. The U/L discriminator switch in the tricell (referred to as register ULS) performs an addition of u + v and tests the result against the 1-volt reference (shown as 1v in FIG. 19). If the sum of u and v is less than one volt, the excursion is in an upper facet; therefore a lower tricell is automatically disabled and an upper tricell functions normally. If the sum is more than one volt, the excursion is in a lower facet; therefore an upper tricell is disabled and a lower tricell functions normally.

An excursion enters a cell if the Buv specified by braider choice register BCH matches that cell's REC. There is no effect if the cell is not within an aperture, or if the upper-lower switch is off. However, if the cell is within an aperture, and the upper-lower switch is on, the cell is allowed to respond freely unless the hex is disabled or there is an adjacent partition.

These conditions are evaluated by the following rules regarding the available signals. (Note that "0" is an enabling condition, "1" disabling.)

If Buv(BCH) specifies the contents of REC, tricell responds

normally:

1. unless AAB and/or ULS =1, in which case it does nothing, regardless of DAB or AJP.
2. unless DAB and/or AJP =1, in which case the tricell halts the braider and sends an alarm.

When the enabling conditions of the tricell exist, as specified, it performs its surface exploration functions.

The following stages of calculation take place in analog or hybrid form within the tricells.

The converter subunit changes the proportionality of input variables uv relative to the size and comparative edge lengths of the particular facet, by the following formulas:

UPPER FACET

$$Cu = \frac{u}{Ds@b1}$$

$$Cv = \frac{v}{Ds@a3}$$

$$Cw = \frac{1 - u - v}{Ds@2}$$

LOWER FACET

$$Cu = \frac{u}{Ds@e4}$$

$$Cv = \frac{v}{Ds@d6}$$

$$Cw = \frac{1 - u - v}{Ds@5}$$

These three components, Cu, Cv and Cw, constitute together a vector Cuvw localizing the original flat-point uv on facet coordinates uvw, converted to the proportionality of the actual facet in scene-space.

The dot product is next found of this vector Cuvw (localized to the coordinates of point @, supplied from centerpost) and the upper or lower conversion matrix, to yield localized point Luvw. In the upper tricell the operation is:

$$Luvw = (Cuvw - @) \cdot \left[ULM\right]$$

while in the lower tricell the operation is

$$Luvw = (Cuvw - @) \cdot \left[LLM\right]$$

Influence coefficients IC are now calculated for the three influence planes. Each tricell must solve three algebraic equations for three influence coefficients.

In the upper tricell these are:

$$(Luvw + IC1 \text{ times } NmUp - @) \cdot If1 = 0$$

$$(Luvw + IC2 \text{ times } NmUp - @a) \cdot If2 = 0$$

$$(Luvw + IC3 \text{ times } NmUp - @b) \cdot If3 = 0$$

In the lower tricell these are:

$$(Luvw + IC4 \text{ times } NmLo - @) \cdot If4 = 0$$

$$(Luvw + IC5 \text{ times } NmLo - @d) \cdot If5 = 0$$

$$(Luvw + IC6 \text{ times } NmLo - @e) \cdot If6 = 0$$

The tricell then calculates raised influence points RIP on the three influence planes.

The formulas used in the upper tricell are:

$$RIP1 = Luvw + IC1 \text{ times } NmUp$$

$$RIP2 = Luvw + IC2 \text{ times } NmUp$$

$$RIP3 = Luvw + IC3 \text{ times } NmUp$$

The formulas used in the lower tricell are:

$$RIP4 = Luvw + IC4 \text{ times } NmLo$$

$$RIP5 = Luvw + IC5 \text{ times } NmLo$$

$$RIP6 = Luvw + IC6 \text{ times } NmLo$$

The tricell then calculates weights W proportional to the relative distance of Luvw from the sides of the facet.

In the upper tricell the formulas are:

$$W1 = \frac{1}{1 - \frac{Ds@b1 - Cw}{Ds@b1}}$$

$$W2 = \frac{1}{1 - \frac{Ds@2 - Cu}{Ds@2}}$$

$$W3 = \frac{1}{1 - \frac{Ds@a3 - Cv}{Ds@a3}}$$

In the lower tricell the formulas are:

$$W4 = \frac{1}{1 - \frac{Ds@e4 - Cu}{Ds@e4}}$$

$$W5 = \frac{1}{1 - \frac{Ds@5 - Cw}{Ds@5}}$$

$$W6 = \frac{1}{1 - \frac{Ds@d6 - Cv}{Ds@d6}}$$

The tricell now calculates surface-point xyz and tangent plane tp.

In the upper tricell the formulas are:

$$xyz = \frac{W1\ RIP1 + W2\ RIP2 + W3\ RIP3}{W1 + W2 + W3}$$

$$tp = \frac{W1\ If1 + W2\ If2 + W3\ If3}{W1 + W2 + W3}$$

In the lower tricell the formulas are:

$$xyz = \frac{W4\ RIP4 + W5\ RIP5 + W6\ RIP6}{W4 + W5 + W6}$$

$$tp = \frac{W4\ If4 + W5\ If5 + W6\ If6}{W4 + W5 + W6}$$

Compound signals xyz and tp then pass, in analog form, out through the xyz and tp lines at the top of the tricell.

The array control devices each have their own system of operation. These will be described separately.

The view calculator, whose inputs and outputs are shown schematically in FIG. 24, operates in any way necessary to compute pq, as is done differently in different commercial units, already mentioned.

The braider's operations are controlled by the array and the main computer, as may best be understood with reference to FIG. 25.

The braider is started and stopped by pulses to the start and stop terminals s6, s7 under control of the computer.

The computer must digitally set a braid-code selector prior to starting the braider. The computer sets the braid-code to a combination of row selections (A, B, C, D in FIGS. 10 and 11) while the output voltages themselves select between upper and lower facets. The computer's braid code selection is accomplished via command-line s30, as will become evident.

The braider sums various signals to obtain the effective uv which it blends into Buv.

The constituent signals contributing to the control-braid components are as follows:

part	constituents
u	ud (if specified) on line s17 plus ua (if specified) on line s16
v	vd (if specified) on line s15 plus va (if specified) on line s14
Du	Dud (if specified) on line s9 plus Dua (if specified) on line s8
Dv	Dvd (if specified) on line s12 plus Dva (if specified) on line s11

Du and Dv are the specified changes in Bu and Bv over a one-microsecond period, supplied as parameters.

These inputs may be changed either digitally (by the computer, on lines s9 and s12) or in analog (by other devices, on lines s8 and s11).

Finally, two "tweak amplifier" inputs to the braider 52, 54 allow the transmission of adjustive voltages to further modify u

and v. These amplify the difference signals Dua and Dva.

The Bu calculator 55 outputs the component u-functions u1 and u2 of the braid at s25 and the Bv calculator 56 outputs the component v-functions v1 and v2 at s26; the interlocked oscillation of these functions, u1 to u2 and v1 to v2, is maintained by a shared 45° phase interlock controller 57. (as illustrated in the code braid graph of FIG. 10),

A stop pulse or command s7 will halt output from the braider at its present values. While it is stopped the input settings s8-s17 may be altered. A start pulse or command s6 will cause it to resume output as the sum of the functions of the new values. A respecify command, which may only be administered after a stop pulse or stop command, causes the braider's input select register (not shown) to be reloaded from the computer, causing the braider to respond to a different combination of inputs.

For every 1 volt increase or decrease in u or v of the summed inputs, the braid changes by one row setting. Circuitry within the recognizer and converter 58 notes such row-crossings as pulses at tally outputs s27, s28 and changes in up-down counter outputs s31, s32. In addition, row-crossing information is naturally a part of the code braid appearing at multilines s18, s19.

The braider control responds to various commands, which arrive as digital 16-bit words on command line s29. The commands are as follows:

0001, start. Same as signal s6.

0010, stop. Same as signal s7.

0011, respecify. This command causes the braider to begin a new braid function according to the contents of the input select register, inter-

nal to the braider, to determine the combination of controls which shall commence to operate it upon the next start pulse. The bits of this register represent the different inputs: an initial uv setting, specifiable either in digital (ud, vd) or analog (ua, va), a difference setting representing the sources of change, whether in digital (Dud, Dvd) or analog (Dua, Dva). The bit positions of the input select register represent, respectively, Dud, Dua, ud, ua, Dvd, Dva, vd, and va.

0100 (+ 4 bits), reset. This command changes the braid range being output as a part of Buva and Buvd.

0101 (+ 8 bits). Reset u count.

0110 (+ 8 bits). Reset v count.

0111 (+ 4 bits). Mesh exception.

The braider in addition responds to mesh irregularities, as signalled in the mesh irregularity bits associated with a given tricell. These will arrive through the command line as part of a "mesh exception" command. At times the system's array action will be halted by a mesh exception. At such time the mesh exception control unit will examine the failing tricell's mesh exception control bits. If this bit pattern indicates a "collapse" or swing connecting two non-adjacent cells as in FIG. 23, 32, 34-38, the

mesh exception bits are sent by the mesh exception controller to the braider on command line s30 (preceded by a warning bit).

The braider then alters its output depending upon the mesh irregularity code it has received. (The first bit of the mesh irregularity code specifies whether the facet is upper or lower.) The braider will then take action as indicated:

Code	Sides Collapsed	Braider Action
Lower facets:		
0001	R to S	u unchanged, v raised to 1
0010	R to T	u raised to 1, v unchanged
0011	S to R	u unchanged, v lowered to 1-u
0100	S to T	v lowered to u, u raised to 1
0101	T to R	u lowered to 1-v, v unchanged
0110	T to S	u lowered to v, v raised to 1
Upper facets:		
1001	R to S	u unchanged, v lowered to 0
1010	R to T	u lowered to 0, v unchanged
1011	S to R	u unchanged, v raised to 1-u
1100	S to T	v raised to u, u lowered to 0
1101	T to R	v unchanged, u raised to 1-v
1110	T to S	u raised to v, v lowered to 0

Example. FIG. 22 shows an irregular mesh; FIG. 23 shows a representation in the standard array of the same irregular mesh, with certain cells void 33 or to be swung across by braider action 32, 34, 35, 37, 38. The codes which will cause appropriate indirect addressing by the braider are also shown in the illustration 0001, 0011, 0100, 0110, 1001, 1010, 1011, 1100, 1101, 1110, as well as an error code which should not reach the braider 1111.

Operation of the twirler TW takes place as follows, as may best be understood with reference to FIG. 26. Oscillations are performed by two sine-wave oscillators 61, 62 held by phase control 63 to being 90° out of phase. Their outputs s39, s40 make a circular, spiralling or looping pattern (if considered on an oscilloscope or as Auv). A halt line s36 instantaneously stops output voltages s39, s40 at their current values. Upon the end of the halt signal, they resume changing with their rates of change synchronized. A pair of "volume control" amplifiers 64, 66 are simultaneously operated by control line s37. Their amplitude setting is controlled by variations of an analog input voltage, making the exploratory circle larger or smaller under control of an analog signal on line s37. A pair of "tweak amplifiers" 65, 67 are simultaneously operated by control line s38. They turn a pulse on line 38 into a momentary increase of both u and v outputs, effectively repositioning the spiralling pattern.

The Pythagorean distance unit, illustrated in FIG. 27, finds the distance between two points in three-space as represented in analog or digital form at inputs s45 or s46 and s47 or s48 by the Pythagorean formula

$$Ds = \sqrt{(x(0) - x(1))^2 + (y(0) - y(1))^2 + (z(0) - z(1))^2}$$

whose result Ds exits the PDU on line s49.

It is so housed and wired that it may be coupled to either a six-part multiline or a four-part multiline. In the latter case, since $z(0) - z(1) = 0$, it computes

$$Ds = \sqrt{(x(0) - x(1))^2 + (y(0) - y(1))^2}$$

which is the formula for distance in two dimensions.

Edge checker EC, shown in FIG. 28, operates by testing whether a certain vector product equals zero, which shows that the two lines represented by the vectors are at right angles. The device dot-multiplies tp, a three-part vector arriving at s56, by the difference vector between xyzLd (supplied at s57 and stored there in a DR) and incoming xyz s58, namely,

$$(xL - x,\ yL - y,\ zL - z)$$

and tests whether their dot product is zero. A voltage signal is always present on the m line out s60, indicating a miss, except while the dot product is zero, when the voltage at s59 turns on and that at s60 stops.

Operation of homing unit HU, shown in FIG. 29, is as follows.

Coordinates of lookout or light LN are set into VC 176 by line s87 and the desired point pqD as seen from LN is set into the PDU 177 on line s88.

The twirler 170 cycles and its signal s80 drives braider 171 to output Buva s70 modulated through a circular pattern, which goes to surface unit array 173 which outputs excursion xyz s71. The spiralling oscillation of Buva s70 drives xyza through a similar pattern on the virtual object. Its view coordinates pq s72 are calculated by VC 176 and the distance of pq (represented by a signal on s72) from pqD (represented by a signal on s88) is computed by PDU 177. A differential analyzer 179 keeps watch over the results of this calculation to determine the instant at which it begins to go up in voltage, indicating an increasing virtual distance between the scene elements represented by pq s72 and pqD s88.

As this distance begins to increase, differential analyzer 179 sends a strobe pulse s75 to a delay line timer 178, which holds it back for 2/3 of a twirler cycle, after which it is referred to the tweak input s77 of the twirler 170. This amplifies the Dua and Dva inputs (not shown) for a brief instant, causing the circular scanning pattern Tuv s80 to move on the virtual surface closer to the projected point represented by pqD s88. This steers the xyz circle s71 closer to the desired point.

Meanwhile, the distance signal s74 from PDU is also sent to an ADC 83 where it is strobed into a digital register by the strobe s75 from the differential analyzer 179. Being then reconverted to analog form by DAC 81, it goes s78 to the volume control of twirler 170 and reduces the size of the twirling circle in proportion to the

nearness of the desired point pqD s88. When the difference between pq and pqD is reduced to 0, the hit has occurred. A signal so indicating leaves PDU 177 on hit-line s73. This signal strobes into digital registers current values of Buv, xyz and pq where they become available in analog s81, s83, s85 and digital s82, s84, s86. Hit-signal s73 also goes to twirler 170 on halt-line s79 and the braider is stopped.

The operation of the reflector, as seen in FIG. 30, takes place in analog circuitry as follows. Inputs xyz1 s90 and xyz2 s91, representing endpoints of the ray arriving at a surface, have their distance measured by a PDU internal to RFL (not shown). This is divided into their vector difference, yielding the unit vector r of the arriving ray. Another vector a is found as the vector cross-product of tp X r.

Two simultaneous equations are then derived as vector dot-products and solved algebraically. These are:

$$b \cdot tp = xyz \cdot tp$$

$$b \cdot a = 0$$

where b is a vector whose first element is either 0 or 1, depending on which yields a solution, and whose second and third elements are the unknowns. The equations are solved for b.

The resulting vector b then passes into another PDU, not shown, which finds its length. The solution ray s93 is found by dividing vector b by the length thus found.

Edge tracer ET may best be seen in FIG. 31. This mechanism works in principle as follows: two scene-points are compared, both on the desired edge, and that which is further along in the tracing-direction is kept. A new edge-point is found for the next comparison.

At the beginning of a cycle, registers in all coholders 110, 112, 113 reset themselves to 0, except for the pq0d register 113a, which holds the value of pq moved to it at the close of the previous cycle. The coholder control (in 113, not shown) is set to its initial state.

The twirler 101 receives a starting pulse s239 from the comparator 114. This causes the twirler oscillators to resume oscillating to produce Tuv s201. Tuv s201 passes to the braider 102, causing Buva to oscillate s202. Buva passes to the surface unit array 104, causing a probe excursion to describe a similar pattern with respect to the surface representation in the holding array 106, which leaves the surface unit array as a signal of form xyza s205.

In addition, the surface unit array 104 outputs the tangent perpendicular tpa of the hit-point, s204. Tangent perpendicular tpa goes to the edge checking unit 103, which performs a calculation in analog to see whether tp passes through the vantage point LN with which the edge checking unit 103 has been supplied. Whenever tp values cross LN the edge checker 103 outputs a tangent hit signal, which goes s203 to the coholder control 111.

Hit-point xyz also passes s205 to the view calculator 107 set to LN, where its projection is calculated in analog form to view coordinates pq. Result pqa s206 reenters the edge-tracing unit ET.

Signal Buva s202 also passes into the edge-tracing unit ET.

The coholder control 111 is triggered by a hit signal s203 from the edge checker 103. The coholder control 111 is capable of two distinct signals to be passed along line s212; these we call a hold 1 pulse and a hold 2 pulse.

The first hit signal s203 causes a convert strobe s213 to the MADCs, there stimulating the conversion to digital form of uv s209, xyz s210 and pq s211. Shortly thereafter the coholder control 111 sends out a hold 1 pulse s212 to the three coholders 110, 112, 113. The second hit signal causes the coholder control to send a convert strobe s213 to the MADCs, then to send out a hold 2 pulse s212 to the three coholders.

Upon receiving a hold 1 pulse from the coholder control 111, the uv coholder 110 stores the present value of Buvd in register Buv1d 110a. Upon receiving a hold 2 pulse from the coholder control 111, the uv coholder 110 stores the present value of Buvd in register Buv2d 110b.

Upon receiving a hold 1 pulse from the coholder control 111, the xyz coholder 112 stores the present value of xyzd in register xyz1 112a. Upon receiving a hold 2 pulse from the coholder control, the xyz coholder 112 stores the present value of xyzd in register xyz2 112b.

Upon receiving a hold 1 pulse from the coholder control 111, the pq coholder 113 stores the present value of pq s211 in register pq1d 113b. Upon receiving a hold 2 pulse from the coholder control 111, the pq coholder 113 stores the present value of pqd s211 in register pq2d 113c.

A hold 2 pulse stops the twirler s214.

As soon as these values have been stored in the coholders 110, 112, 113, the Pythagorean Distance Units 108, 109 convert to analog form the numbers stored in pq0d 113a, pq1d 113b and pq2d 113c, and calculate their Pythagorean distances Ds01 and Ds02 in analog. These values return to the ET s207, s208 and go to comparator 114. Comparator 114 then compares the values of Ds01 and Ds02. If Ds01 is larger, an s225 pulse is sent to the uv coholder 110, the xyz coholder 112 and the pq coholder 113; if Pd02 is larger, an s226 pulse is sent to the uv coholder 110, the xyz coholder 112 and the pq coholder 113.

The uv coholder 110 transmits the contents of Buv1d 110a to the uv output register s227 and to the Braider digital input s239 if it receives an s226 pulse. It then sets 110a and 110b to zero.

The xyz coholder 112 transmits the contents of xyz1 112a to the xyz output register if it receives an s225 pulse, and transmits the contents of xyz2 112b to the xyz output register if it receives an s226 pulse. It then sets xyz1 and xyz2 to zero.

The pq coholder 113 transmits the contents of 113b to 113a if it receives an s225 pulse, and transmits the contents of 113c to 113a if it receives an s226 gate pulse. It then sets 113b and 113c to zero.

The comparator 114 then sends out a new starting pulse s239 to the twirler 101. The uvd sent to the braider s239 furnishes a new starting point for the next excursion.

Operation of the slicer is as follows, with reference to FIG. 3a

The q-checker 135 is preset with a digital value k s260 or s265, representing a plane in the view coordinates of the slicing VC(LM) 126. Incoming qd s264 from the slicer VC 126 is continuously compared with k, stored in 135a, and the q-checker 135 sends out a strobe or "q pulse" s269 whenever it finds q equal to k. By feedback the excursion is kept along this line k.

At the beginning of the slicer's operating cycle, all registers in units 130, 132, 134 and 135 are set to 0, except for the p0 register 134c, which holds the contents moved to it at the close of the previous cycle. The p-control 134 is set to its initial state. View calculator 126 is set to LM, the point of origin for the slice viewed as an edge in pq-coordinates. View calculator 128 is set to LN, a point of origin from which a slice is to be viewed. The q-checker 135 is preset to an initial value of k which is entered in the SL by analog s259 or digital means s260, and stored in the k-comparison register 135a.

The twirler 250 receives a starting pulse s290 from the starter 129. This causes the oscillators of TW to resume oscillating to produce Tuv s250. Tuv passes to the braider 121, causing Buva to oscillate s251. Buva passes to the surface unit array 123, causing a probe excursion to describe a similar pattern on the surface represented in HRA 125. The probe hit-signal xyz leaves the surface unit array in the form xyza s254.

Hit-point xyz s254 goes to two view calculators 126, 128. Each view calculator calculates points pqa from xyza. Output pq_1^{s255} of view calculator 126 is separated by a dividing coupler 127 into components p s256 and q s257, which enter SL from slicing view

calculator 126 and after conversion to digital form go to separate subunits, q to the q-control 135 on line s264 and p to the p-control 134 on line s263.

When q is found by the q-checker 134 to equal k, it issues a q pulse s269. The q pulse s269 causes the starter 129 to stop the twirler 120, uvd s251 from the braider 121 to be accepted into the uv register 130, xyzd from the surface unit array to be accepted into the xyz register 132, pd to be accepted into the p1 register 134d of the p coholder 134b, and picture-point pqLN to be accepted into the pq register 139.

The p-compare unit 134 now compares p1 in register 134d with p2 in register 134c and acts according to the following rule:

Current sign of p-compare unit 134	Condition	Action
+	$p1 > p0$	transfer pulse s271 to uv register 136, xyz register 132, pq register 138, followed by erase pulse s272
+	$p1 < p0$	erase pulse s272 to uv register 136, xyz register 132, pq register 138
-	$p1 > p0$	erase pulse s272 to uv register 136, xyz register 132, pq register 138
-	$p1 < p0$	transfer pulse s271 to uv register 136, xyz register 132, pq register 138, followed by erase pulse s272

After sending out a transfer pulse s271, the p-compare unit 134a transfers the contents of p1 register 134d to p2 register 134c, sets p1 register 134d to 0, and sends a resume pulse (not shown) to the starter 129. After sending out an erase pulse s272, the p-compare unit 134a sends an erase pulse s272, the p-compare unit 134a sends a resume pulse (not shown) to the starter 129.

An edge checker 122 keeps track of tpas253 from the surface unit array 123. Whenever tpa symbolically crosses lookout L, EC strobes flipper 131 s252, a switch-sign pulse s267 goes from the flipper 131 to the p-compare unit 134a, which switches the curren sign of its analysis from positive to negative or vice versa. Th corresponds scenically to the probe's going around a corner to a recurved area of a surface.

The aperture control works as follows:

A succession of u+ crossings causes an alternation of b and c IAS pulses; a succession of u- crossings causes an alternation of f and e IAS pulses; a succession of v+ crossings causes an alternation of a and f IAS pulses; a succession of v- crossings causes an alternation of c and d IAS pulses.

These determine four states of the IAS control register (not shown), according to the varying states of two flip-flops. The IAS control register is always in either state A or B, as determined by the first flip-flop, and always in either state C or D, as determined by the second flip-flop. Its behavior is determined by the register as follows:

Pulse from braider	Reaction if in: state A	Reaction if in: state B
u+	b pulse and switch to B	c pulse and switch to A
u-	f pulse and switch to B	e pulse and switch to A
	state C	state D
v+	a pulse and switch to D	f pulse and switch to C
v-	c pulse and switch to D	d pulse and switch to C

Operation of the irregularity control (IRC, not shown) is as follows:

A cell alarm from a tricell halts the braider and readies the irregularity control to receive a two-bit irregularity code, which is then shifted out of the cell on the hex-out line (11 in FIG. 14) and accepted and examined by the irregularity control. The code is automatically produced by the hex logic during the shift-out. It is as follows:

00	no alarm
01	cell disable bit on
10	invalid-curve bit on
11	mesh exception

If the code is 01 or 10, the irregularity control interrupts the computer, which then attends to the needs of the cell by shifting or additional loading of the array. If the code is 11, a four-bit mesh irregularity code next comes out the hex-out line, and is accepted by the irregularity controller.

The irregularity controller then examines the bit pattern and directs computer action as indicated below. Any other bit pattern is sent to the braider.

0000	ignored
0111	indirect (stop braider; transfer control to computer. Computer reads braider location, goes to mesh exception table, reloads braider with new address from table and shifts aperture and braid code to indicated cell, and restarts braider.)
1000	go to subroutine. (Addressed by cell and edge number in digital subroutine table.)

(Computer is interrupted, goes to special program for handling particular cell.)

1111 void (interrupt CPU; error condition if encountered.)

4

The operations creating the tables and lists will now be discussed.

The mesh table is given.

The facet table is created by a computer program which borrows its contents from the mesh table (facet no., head point no.) or calculates them from these mesh-table data (lower or upper, center location, maximum bulge (approximated here by $\frac{1}{2}$ the length of the facet's longest edge)).

The data web table is created by a computer program. This program ascertains the other points required to make upper and lower facets by following in the mesh table according to the direction rules for these facets.

To supply the data for surface generation, the following quantities are calculated digitally by the master computer:

1a. The length of edge 2, Lg2:

$$Lg2 = \sqrt{(x@a - x@b)^2 + (y@a - y@b)^2 + (z@a - z@b)^2}$$

where the expression x@a refers to the location of @a on the x dimension, and similarly for the other reference points and the dimensions y and z. This notation will be used hereafter.

1b. The length of edge 4, Lg4:

$$Lg4 = \sqrt{(x@ - x@d)^2 + (y@ - y@d)^2 + (z@ - z@d)^2}$$

1c. The length of edge 6, Lg6:

$$Lg6 = \sqrt{(x@ - x@e)^2 + (y@ - y@e)^2 + (z@ - z@e)^2}$$

The lengths of the remaining edges may be obtained from the records associated with the adjacent facets, viz.: Lg1 (Lg4 of facet Up1), Lg3 (Lg6 of facet Up3), Lg5 (Lg2 of facet Lo5).

2a. The unit normal vector of the upper facet, NmUp:

$$NmUp = \frac{(@ - @a) \times (@ - @b)}{Lg1 \text{ times } Lg3}$$

2b. The unit normal vector of the lower facet, NmLo:

$$NmLo = \frac{(@ - @d) \times (@ - @e)}{Lg4 \text{ times } Lg6}$$

3. The influence planes between the facets, If1, If3 and If5:

$$If1 = \frac{NmUp + NmUp1}{2}$$

$$If3 = \frac{NmUp + NmUp3}{2}$$

$$If5 = \frac{NmLo + NmLo5}{2}$$

4a. The upper localizing matrix ULM, of nine quantities:

$$\begin{bmatrix} \frac{x@ - x@a}{Lg1} & \frac{x@ - x@b}{Lg3} & \frac{x@a - x@b}{Lg2} \\ \frac{y@ - y@a}{Lg1} & \frac{y@ - y@b}{Lg3} & \frac{y@a - y@b}{Lg2} \\ \frac{z@ - z@a}{Lg1} & \frac{z@ - z@b}{Lg3} & \frac{z@a - z@b}{Lg2} \end{bmatrix}$$

4b. The lower localizing matrix, LLM, of nine quantities:

$$\begin{bmatrix} \frac{x@ - x@d}{Lg4} & \frac{x@ - x@e}{Lg6} & \frac{x@d - x@e}{Lg5} \\ \frac{y@ - y@d}{Lg4} & \frac{y@ - y@e}{Lg6} & \frac{y@d - y@e}{Lg5} \\ \frac{z@ - z@d}{Lg4} & \frac{z@ - z@e}{Lg6} & \frac{z@d - z@e}{Lg5} \end{bmatrix}$$

5. The distances between each reference point and the opposite edge within the facet. We use here the expression "Ds p N," where p is the name of a point in the facet, expressed in @-notation, and N is the opposite edge.

$$Ds@2 = \sqrt{\frac{\{(@ - @a) \times (@b - @a)\} \cdot \{(@ - @a) \times (@b - @a)\}}{(@b - @a) \cdot (@b - @a)}}$$

$$Ds@a3 = \sqrt{\frac{\{(@a - @) \times (@b - @)\} \cdot \{(@a - @) \times (@b - @)\}}{(@b - @) \cdot (@b - @)}}$$

$$Ds@b1 = \sqrt{\frac{\{(@b - @) \times (@a - @)\} \cdot \{(@b - @) \times (@a - @)\}}{(@a - @) \cdot (@a - @)}}$$

$$Ds@5 = \sqrt{\frac{\{(@ - @d) \times (@e - @d)\} \cdot \{(@ - @d) \times (@e - @d)\}}{(@e - @d) \cdot (@e - @d)}}$$

$$Ds@d6 = \sqrt{\frac{\{(@d - @) \times (@e - @)\} \cdot \{(@d - @) \times (@e - @)\}}{(@e - @) \cdot (@e - @)}}$$

$$Ds@e4 = \sqrt{\frac{\{(@e - @) \times (@d - @)\} \cdot \{(@e - @) \times (@d - @)\}}{(@d - @) \cdot (@d - @)}}$$

The view table, which is LN-specific, is computed for each LN as follows: pq is obtained from a VC/LN; distance from LN is obtained by the Pythagorean Distance Unit, with one input set at LN and another to the specific point; center distances for the facets are obtained similarly.

The enclosed centerpoints are obtained by creating a temporary list of pqLN for all centerpoints, and testing algebraically whether each pq falls within an area bounded by pqLN of the three corner-points of the respective facets.

The mantle list is created as follows:

The edges to be recorded in the mantle list are typically irregular and unpredictable, and so must be sought with processes insensitive to this unpredictability.

Plotting is started at the nearest facet to LN. Plotting takes place at facet boundaries until the edge is reached according to EC/LN.

Edge process. The edgetracer is started. The drop-point with the same pqLN on the further surface data web is found; HU follows ET(LN) from this point.

Edges enLN and efLN are traced. All facet boundary-crossings encountered on enLN and efLN cause a braider interrupt and computer interrupt and their Auva from braider and braider count is logged.

Plotting is continued around edge till end. If edge ends without rejoining point where edgetrace began, return to that point and go in other direction, logging events until edge is completely logged. End edge process.

Each edge being traced is resolved twice, once at each end; an edge is resolved if it is discovered to be part of another edge already under study, or terminates at a jut, a fold (where it smoothes out and upper edge fuses with lower) or an interference. Only if the edge is circular and non-terminating does it not end twice in one of these.

All elements are logged as two simultaneous entries, Bivd and xyz, in the form shown earlier.

Disappearance of a jut. If lower edge checker signals a hit, that location is logged as a jut termination of lower edge,

and its lower edge for the same pqLN is found on a further edge and logged as well.

Interception by a jut. Either enLN or efLN may be intercepted by a jut. All web-areas which come near the edge are bypass-checked If an intercept occurs, it is logged as a jut and the new uv on that jut serves as a new starting place for enLN or efLN, depending on which was occluded.

If enLN has been occluded, the new edge must be completely traced and logged. If efLN has been occluded, its jut-point becomes the starting-point for a new efLN excursion.

Edge process is performed for all juts which have their other ends already resolved. Edge process is repeated for all edges of object. All processes are repeated for each additional object in scene. Logged points are reordered, gathering separately acquired edge-segments into correct edge-sequences by DsLN. These points are then renumbered in ascending order of distance of their nearest event from LN.

Mantle table entries are sorted by increasing distance from LN.

Creation of the encounter list is intricate. The problem is to find the pqL curves of edges enL and enLN, efLN for all LN-except-L, and the pqL curves of ec for specific color-thresholds, and list their intersections, upturn-points and downturn-points in a useful order, except for those invisible to L. While certain of the intersections may be found from the mantles, others cannot, nor can their interrelations in coordinates pq.

The intersections of the different en and ef curves are found by different methods, as specified in the following table. In the cases not already available from mantles ("M" in the table), the intersections are found by a hit-signal from an edgechecker.

	enL	efL	enL1	efL1
enL	Given by M/L	Given by M/L	ET/L1 followed by EC/L	ET/L1 followed by HU/L1 (further web) followed by EC/L
efL	—	Given by M/L	ET/L followed by HU/L1 (further web from L) followed by EC/L1	ET/L followed by HU/L1 (further web from L) followed over by VC/L followed by HU followed by EC/L
enL1	—	—	Given by M/L1	Given by M/L1
efL1	—	—	—	Given by M/L1

All these intersections are ascertained, their curve types noted, and they are set aside in a temporary list; except that all nodes are compared with those previously listed to avoid listing a node more than once.

Color-edges having some predetermined color value are obtained by algebraically determining these edges of equal color from the color-system and playing the corresponding Auv through the array. The output signals xyz and tp then go to two edge checkers, EC/K (K for color) and EC/L1, which fire "hit" signals when ec touches enLM and enLN.

Intersections of ec with efL are obtained by bypass checking and following over ec on L-nearer webs, and monitoring this output with EC/L; a hit signal indicates an intersection. These are added to the temporary list.

Intersections of ec with efL1 are obtained by bypass checking and following over ec on L1-nearer webs, and monitoring this output with EC/L1; a hit signal indicates an intersection. These are added to the temporary list. A record is kept of each color-edge which intersects with no other edge, and a starting point is saved for it. A record is kept of each L-edge and L1-edge which intersects with no other edge, and a starting point is saved for it.

All edges are now retraced and played through VC/L, starting at their intersections or saved starting places, and pqL is monitored. Intersections encountered (by monitoring of pqL and comparison with pq's of the temporary list) are assigned their corrrct relative curve positions. In addition, pqL is compared against a qL-watching differential analyzer for upturn and downturn nodes, which are added to the temporary list.

When all nodes have been recorded in this manner, the final encounter list is created from the temporary list by sorting all nodes according to positional pq and curve continuity.

Color assignment between curves is done according to some function of the color table.

All scene-analytic picture processes require certain supporting processes, namely that the array be loaded and set, array control devices be set, an excursion be started, and all chambers be supplied. The operational meanings of these terms are as follows.

To load an array, the computer shifts a data web row-by-row into the hexes through the jumper system.

To use less than the whole array, the computer shifts into the array a pattern of partition bits to create a chamber, then loads a data web row-by-row into the hexes within that chamber.

To set a chamber to a given address; the hex cells are filled with a data web, including recognizer settings, having that address near its center; the Braider tallies are set to 0 and the starting cell of this zero-count recorded by the computer; an aperture pattern is loaded into the chamber and shifted to surround that address; Braider is set to the specified uv.

To set an array control device, especially VC, HU, ET or SL, it is supplied with an LN by the computer.

In addition, specific devices may be "set" with other quantities, e.g. the HU with a pq.

To start an excursion, with a chamber and its associated control devices set, a start command is sent digitally to the Braider and Twirler.

To supply a chamber, the computer supplies a chamber by continually keeping it filled with usable data. When interrupted by a Braider halt at a curvature-invalid cell adjacent to a border or partition, the computer shifts the data array so that the probed facet is nearer the chamber's center. The computer then adjusts the Braider tallies, restarts the Braider and fills with data those cells which have been emptied of data by the shift.

In this embodiment of the invention, the component scene-analytic picture processes are raysearch, edgetracing, dropsearch, following (including following nearer and following farther), bypass checking, edge guarding, LN-edge tracing (including upper shadow edge tracing and lower shadow edge tracing), and color edge tracing. We shall detail these in turn.

The process of raysearch is investigating the hit-point of a given ray from an LN; "find," in the raysearch context, means ascertaining that hit-point. This is the method: set HU to LN and set HU also to follow pqLN of desired ray; start Braider and Twirler till HU hits.

The process of edgetracing consists of setting an edgetracer to an edge and causing an excursion along that edge by means of Braider, Twirler and other devices.

The process of dropsearch is the process of finding a hit-point beyond an edge-point xyz found on web A with reference to an LN. This is the method: send xyz to VC(LN); send resulting pq to HU(LN), searching in chamber containing farther web than A.

"Drop to" in the dropsearch context means find and/or follow a pqLN on a specific farther web from LN than that supplying the pq.

The process of following an excursion $\overset{xyz}{\wedge}$ consists of sending the excursion to VC(LN), taking resultant pq to HU(LN) at another web to find a different xyz and/or uv.

The process of following another pair of variables, esp. pq, consists of feeding resultant pq (as in previous paragraph) as coordinate specifiers to HU(LN) at another web to find xyz and/or uv.

The process of following between or following nearer consists of following on a nearer web than that from which is acquired the pq or xyz being followed.

The process of following beyond or following farther consists of following on a farther web than that from which is acquired the pq or xyz being followed.

The process of bypass checking is used to determine whether a specific line in space intersects with the surface corresponding to a given facet. It is performed as follows.

A loaded array is connected to an HU which is set to a specific pq representing a line in space. The homing unit HU directs an excursion to ascertain whether pq hits the facet. TW is used to drive BR over the entire surface. If no hit signal is returned, pq does not hit the surface.

A multi-stage bypass check may be performed when several juts are in a certain pq-neighborhood as seen by a view calculator.

The bypass check is performed successively in chambers wherein are represented the surfaces at different levels of distance.

The process of edge guarding may be used to inform as to whether a probe or a television scan departs from an object across its edge. When used from LN-except-L, it gives indication of the shadow-status of an object with respect to LN-except-L. This HU is attached to a loaded array, with VC(HU) and EC set to LN. HU is given as input the view coordinates pq from some excursion (or, if television, the x and y voltages of the TV raster-scan). When EC signals that tp has crossed the vantage, the scan is outside the object's outline.

There are several processes o f LN-edge tracing, depending on whether LN=L and whether the near or far edge is being traced. The case for LN= L will not be separately described, as the general method will work.

The process of tracing an upper shadow edge is performed as follows.

Set ET to LN-except-L, and send its output xyz to EC(L) and VC(L). Output pq of VC(L) will be upper shadow edge. Start edgetracing with EC(LN-except-L) on near side of edge; send xyz and tp to EC(L) and xyz to VC(L). When EC(L) signals hit, output has gone on other side of object, continue tracing; next EC(L) hit indicates reappearance of en(LN-except-L) on near side of object. EC(L) hit-signals indicate ends and beginnings

of shadow edge on near side of object. Bypass check nearer webs; if hit on nearer web, edge becomes invisible; follow on nearer webs till hit ceases; edge is now seen again.

The process of tracing a lower shadow edge is performed as follows.

Set ET to LN-except-L, follow on further web with HU(LN-except-L), send xyz output of HU to VC(L), EC(L). Start edgetracing on edge. If there is no interference, pq from VC(L) is lower shadow edge. Perform bypass check on all near facets; if interference follow over with HU(L).

The process of following a color edge is as follows.

Go to color table, evaluate succession of values uv giving equal color according to expressions in color table. These expressions are evaluated algebraically by digital computer, to ascertain equicolor boundaries. The resulting stream of control variables uv (representing equicolor boundaries) is sent to the array; array output xyz is sent to VC/L; output pq is color-edge. Check for interference by means of bypass check; if it occurs follow over until interference ends. Also check xyz stream with EC(L); after hit signal from EC(L), indicating that xyz has gone to backside, suspend output but continue trace. On next EC hit resume output. Suspend and resume outputs on alternate EC hit signals.

In the cathode-ray tube surface embodiment, analog functions (such as the vertical curved profiles of the raised boundaries between surface shells of adjacent triangular facets) are stored pictorially on the surfaces of said cathode ray storage tubes and explored by means of computer-controlled steering of readout cathode rays during a probe. In such an application, the faces of the cathode-ray storage tubes have short curves drawn on their surfaces by a "write" beam, in assigned positions of normalized length. Probe Luvw then provokes the exploration of these profiles by the "read" beams, so as to ascertain the corresponding heights of the edge-arches at that point as parameters for the surface generator. For instance, if the normalized u, v and w of an upper facet were equal to .2, .3 and .5 respectively, the heights of arches representing edges 1, 2 and 3 would be searched by read beams at .2, .3 and .5 of their horizontal widths respectively. These heights would then serve as parameters for a localized curvature function similar in principle to that employed in the main embodiment described in this application, but one creating curvatures over the edges as well as the areas of the facets, like the improved arch-edged surface functions also described.

In a further extension of this method, four-sided and n-sided facets and surface sections could be used. In an alternative surface system likewise within the scope of this invention, the CRTs store not the arch profiles but the tangent perpendicular vectors at the facet edges, each represented by a set of curves on the storage CRT; curves x, y, z representing x, y and z components of a tilting If vector on a facet edge of normalized length. Vertical oscillating deflection of a cathode-ray read beam searches the values of x, y and z. For instance, positioning of the vertically oscillating search beam at a position .75 along the curves will permit the readout of x, y and z values of the vector as the beam crosses their respective curves.

The operation of the color system is as follows. To ascertain the native color of a hit-point xyz, irrespective of shadow, the computer consults the color table above, bringing as an argument to the table flat-coordinates Auvd, and tests Auvd in the expressions of the loci. When the relevant loci of Auvd have been determined, the corresponding color-expressions or albedo are evaluated, yielding a brightness-value, representing plain albedo, or a three-part vector, which we may call rgb, representing the color of point xyz.

In the alternative color system already mentioned as employing a storage CRT, operation is somewhat different.

Using a random-access point-plotting computer display control, such as the Digital Equipment Corporation Model 338, the computer in an operation prior to array manipulations writes upon the respective storage tubes the red, blue and green components of coloration. During array manipulations or when shaded or colored output is required, the point-plotting display control directs the storage-tube read beams to examine parts of the flat map Auva stored on the surfaces of the tubes. The relative brightness at the particular point or zone examined would correspond to the native shading or a color-component of xyz, irrespective of shadow.

The picturemaking and output processes employ the scene-analytic processes upon the array and other systems to obtain pictorial and other data which may control the system's output devices and appear, through these output devices, in output pictures.

These processes include processes for making preset-array point-by-point halftone, random-plot halftone, half-tone television by raster-following, line drawing, non-shaded TV line drawing, taper-shaded TV line drawing, shaded or color-filled TV line drawing, videotape or video disk recording or delayed television, stereo pairs, lenticular 3-D output, and hologram output.

A preset-array point-by-point halftone plot is used when a regular array of colored or shaded points is desired, for example to make a half-tone printing-plate with a conventional regular dot array.

The main computer, through a program, selects the number of dots desired in the horizontal and vertical dimensions of each picture and divides these into the width and height of the desired picture, respectively. This yields the separation distances of the picture-points. A pair of numbers corresponding to the position of the first point in the picture to be filled then becomes steering coordinates for a homing excursion, said pair of numbers being pqL for the picture.

Routine. These numbers are set to the pd and qd inputs of the homing unit. The homing unit is turned on and started at different surfaces within the scene, successively more distant from L, until a hit-point xyz is found. The color of that hit-point is then ascertained by looking up the Auvd corresponding to xyz in the color table and computing the color of that point. The color is then transmitted to an output device, where it is used to fill a point in a picture spatially corresponding to the position of the point in picture-coordinates pqL.

If the picture is finished, the computer goes on to the next picture.

If a row has been filled, the computer then adds a row's distance to q, resets p to its first value and begins again (from routine, above). If a row has not yet been filled, it adds a column's distance to p and begins again from point routine.

The process of random-plot halftone produces a half-tone photograph whose constituent points are irregularly disposed about the picture, like grains in a photographic emulsion, rather than regularly arranged as in a printing halftone. This is of use when creating photograph-like pictures and motion pictures, where an exact preset or regular array of dots is undesirable.

Points are plotted from the facets in proportion to the relative size of the object. The relative size may be conveniently determined by the sine of the object's angle to the viewer and varies inversely with the square of the distance.

The number of points to be plotted is multiplied by a weighting factor based on the area's angle. A good weighting factor is the sine of the angle of tp to the line from L to xyz.

This may be facilitated (for example) by dividing each pair of facets (upper and lower) into 100 zones and calculating tp for the midpoints of each one of them.

After setting Bd to select a pair of facets, the computer sets u and v successively to all permutations of the midpoints given in the following table, and creates a temporary list of their respective tp's:

zone	midpoints
0 to .1	0.5
.1 to .2	1.5
.2 to .3	2.5
.3 to .4	3.5
.4 to .5	4.5
.5 to .6	5.5
.6 to .7	6.5
.7 to .8	7.5
.8 to .9	8.5
.9 to 1	9.5

All 100 flat-coordinate pairs uv are sent to the array and their tp's recorded.

The sine of these tp-values to the line from L to xyz is calculated digitally by the computer and stored in a corresponding table.

A series of random or pseudo-random uv pairs is then plotted in the 100 squares between the zone boundaries in u and v.

To each midpoint pair there corresponds a pair of zones (given by the above table).

Within each uv square, the number of random or pseudo-random uv points is proportional to the sine and inversely proportional to the square of the distance, viz:

$$\frac{x}{N} = \frac{\text{sin of tp to view-line}}{d^2}$$

and where d^2 is

$$(xL - x) + (yL - y) + (zL - z)$$

Coordinates xyza and pqa are also sent to VCs with homing units attached to other chambers, which are set to examine surfaces which may intercept the plotted points: i.e., facets whose center-points are within the "contained centerpoints" list of the facet list for a current facet and its adjacent facets, and which are on L-nearer webs. If any plotted point's ray, so determined, also has a hit-point on a nearer surface, it is not plotted.

Otherwise the computer goes to the coloration table, evaluates the color of the point, and sends it with its pqa/L coordinates to a DMAC and thence to a suitable output device, such as three General Dynamics SC-4400 film plotters recording three separate films for red, blue and green.

A line drawing may be made and sent to an oscilloscope, computer cathode-ray display, computer graph plotter, or other x-y plotting output device.

It may be composed of curves representing any or all the following: enL; enLN-except-L (upper shadow edges); efLN-except-L (lower shadow edges); and ec.

Each edge is traced completely if a transparent-seeming object is desired; otherwise the plotting is opaqued during interference and on the far side, as indicated by ec.

VC(L) outputs pqa to the xy inputs of a final output device requiring analog xy (such as an oscilloscope), pqd to the input of a final output device requiring digital xy (such as a Calcomp plotter or IBM 2250 display).

A television picture may be created by a raster-following method, following the horizontal and vertical oscillators of a television system as p and q input to an HU(L), and taking uv from HU(L) to the color system. Color g or rgb thence goes to the brightness or color system of the television system. (Naturally, if only line pictures or line animation are desired in the television image, all that is basically required is pulsing of the video brightness system at edge-crossing times of the uv-excursion driven by the horizontal oscillator.)

Horizontal and vertical control signals of a television system are followed by homing units HU(L), in different chambers for non-contiguous webs or sections of the same web.

Which webs will be encountered may be ascertained from the encounter list; separate chambers are used for each web separated by a curve enL as specified by the encounter list.

If shadows are desired in the picture, xyza of HU(L) is sent to units VC(LN-except-L), following on all nearer webs to VC(LN-except-L). When no hit occurs on these webs, xyz is out of shadow and output pq correspondingly brightened on the color system; when a hit occurs xyz is in shadow and output pq is darkened.

Resulting uv found by HU goes to color system. Resulting gray-level or color is transmitted to television brightness or color subsystem.

A number of output processes are associated with a device we may call the TV raster controller. These processes produce line drawings electronically converted to a television or scanwise output.

The TV raster controller or TVRC, whose component parts and signal paths are shown in FIG. 34, is an electronic mechanism which ascertains when a television scanning pattern or raster crosses horizontal picture-positions being supplied by another device, and takes prearranged actions, producing brightness signals for controlling video or scanwise halftone. Its inputs include encounter list information, mantle information, empirical curvature information derived from the array, and combinations thereof.

The TVRC may thus be used either for the types of pseudo-photography with which we have been so far concerned in the bulk of this document, or, in another type of employment, for the convenient production of Disney-type "cartoons," animated drawings without precise simulation of reality by means of a three-dimensional data structure.

FIG. 34 schematically illustrates the TVRC and its environment, including main computer 300, data pool buffer 301, and data distributor 302, attached on the one hand to view calculators VC and on the other to raster checkers 303, 304, 305, 306, each composed of a horizontal-coordinate register HCR, a color register and a "free" bit. These raster checkers 303, 304, 305, 306 are attached by comparison lines s518, s519, s520, s521 to horizontal clock 307, and by output lines s522, s523, s524, s525 to color controller 308, in turn itself attached to television system 309.

Operation. In pseudo-photographic mode, view calculators VC are assigned to the tracing of significant lines in the picture as determined by the encounter list; the VCs are controlled by edgetracers and homing units set to operate in synchronization with the downward movement of the video line-scan of the TV system, so that q of their downward scans is always approximately equal to q of the TV system's vertical oscillator. This is equivalent to a downward "crawl" by the VCs along all curves in the picture in synchronization with the vertical sweep of the television system. The TVRC converts these excursions to pulses which integrate to form a picture.

The VCs are assigned to given edges in the picture by the main computer. The computer ascertains from the encounter list those curves to be encountered on a given horizontal level. (Starting and finishing nodes are determined at the correct vertical heights from the encounter list.)

At a starting node, one or two VCs are assigned to a given line-to-be in the picture, depending on whether the node is an origin of one or two down-moving lines.

Output pq of each VC is coupled to a raster checker 303, 304, 305, 306 assigned to that VC by the computer. The view calculators, driven to horizontal coincidence with coordinate q of the TV system by means not shown, divulge their pq excursion traces to the TVRC by lines s506, s507, s508, s509, said signals being thereat converted to digital form s510, s511, s512, s513, the most recent value of which is always stored in the HCR of the assigned raster checker 303-6.

The crosstime in each HCR is continuously compared with the horizontal clock, 307, a register which counts from 0 to 1023 during each horizontal sweep of the TV system. When the contents of an HCR equal the setting of the clock, the raster checker 303-6 releases the contents of its color register to the color control 308, together with a synchronizing pulse. Since in this particular use the color register has no contents, only the synchronizing pulse is received.

Coordinate q thus achieving satisfactory coincidence with q of the TV system as judged by clock 307, the color control at once sends a pulse to the television brightness circuit, causing a flash of light on any TV screen attached to the TV system.

These pulses will in the aggregate trace the desired line-drawing in the TV output.

At each new q, the encounter list is consulted by the computer. When a node is on the encounter list at that level of q, the computer arranges the addition or deletion of chambers, devices (including VCs) and raster checkers for the increased or decreased number of lines in the output picture.

As the scanning pattern arrives at each node on the encounter list, the computer ascertains whether any new curves begin at that node, and attaches output registers whose free bits are 1, that with the lowest number first, to devices set to control and trace those curves (HU, ET, etc.).

As the scanning pattern arrives at each node on the encounter list, the computer ascertains whether any curves have terminated at that node, detaches their corresponding output registers and sets them to 0, and sets their free bits to 1.

A variant method time-shares a number of raster checkers among a greater number of lines, with assignment of VCs to raster checkers temporary within a line-scan.

Upon the readout of color control signals to the color controller 308, the divulging raster checker is cleared. The exhausted raster checker then has its free bit set to one to indicate that the register is free. The distributor 302 then informs computer 300 that the source VC is no longer in use (through means not shown), whereupon computer 300 reallocates the freed VC to its next edge-following task, through means not shown. The next pq-value s506, s507, s508, s509 having the lowest q is then assigned by distributor 302 to the first available raster checker 303, 304, 305, 306, whose free bit is reset to 0.

At the completion of a line's scan, the system behaves as otherwise described.

In a related approach, using the TVRC to generate a cartoon-like picture which may be unrelated to any simulated three-dimensional scene, only an encounter list and curve-increment data are used with the TVRC, the array being unnecessary.

The encounter list for such a cartoon has substantially the form indicated previously for encounter lists. However, it is not necessarily derived from scenes represented in the array, but may be obtained by other means, such as an empirical analysis of the curvature of drawings. With each curved line in the encounter list must be associated, in addition, a specification of its horizontal increments and decrements, and at what altitudes they occur.

For the use of this method, HCRs can be registers capable of incrementing and decrementing by remote signal.

Curved lines to be encountered are stored in encounter data pool 301 and assigned by distributor 302 to raster checkers 303, 304, 305, 306, such assignment taking place as already described.

Comparison of HCRs with clock 307 takes place as already mentioned. The brightness system 309 is pulsed on clock-match with encounter crosstimes as already described s526.

After a raster-checker has signalled its match, computer 300 sends it increment or decrement pulses on line s500 to reset its value to that of its curve's intersection with the next horizontal sweep.

Another process may use similar equipment to produce a shaded or color-filled TV line drawing ("cartoon" or "animated cartoon" of the familiar type).

This process is like that of non-shaded line drawing, as performed with the TVRC, except that the computer assigns a set of color-values g or rgb to each raster checker (303, 304, 305, 306 in FIG. 34).

When the contents of an HCR are found to equal the contents of the horizontal clock 307, the contents of the color register of that raster checker go to color controller 308 and thence to the television system 309 (to the brightness control if g, to the color system if rgb). The television's output brightness or color is then switched to that value, and remains at that value until the next switching event.

The color-values g or rgb assigned by the computer to raster-checkers are obtained from the encounter list.

A species of line drawing having an appearance of depth or roundness may be achieved by a system like those above which switches brightness slowly.

In this case the color registers may be set to one of two values, "brighter" and "darker" (signified by 1 and 0). The color control 308 is supplied with two devices, which we may call the up-trigger and the down-trigger. The up-trigger, which is fired when the color control receives a signal of 1 from a raster checker, sends a rising voltage pulse, and remains at the higher voltage; the down-trigger, which is fired when the color control receives a signal of 0 from a raster checker, sends a falling voltage pulse, and remains at the lower voltage.

The brightness pulses and values from the color control 308 go to the brightness or color system of the television system 309 and result in a picture having a semblance of roundness.

The computer assigns the above color values of 1 and 0 to left and right edges of an object, respectively, as seen from L.

If the color control receives two consecutive 1 pulses, the second causes a rising voltage which decays to the previous level in twice the rise time; if the color control receives two consecutive 0 pulses, the second causes a falling voltage which rises again to the previous level in twice the fall time. (Thus there are only two stable voltage levels, "up" and "down.")

It is also possible to defer or record television images such as those described.

As in television by raster-following, a homing unit set to L follows a series of horizontal sweeps progressing downward over the picture-area. The stream of flat-points uv determined by hit-points xyz goes to the color system; color g or rgb is sent to the output device. Alternatively, mechanisms such as the TVRC, and methods such as its associated processes, may be employed to make the video recording.

In these applications, however, a delay may occur in the chain, with such intermediate vector-values as pq, xyz, uv or rgb being temporarily stored in some storage or delay device, such as core memory, delay line or shift register.

In the case of delayed television, the output of the delay or storage device to the brightness or color system must be synchronized to the television scan system, whereas its input need not have been.

In the case of videotape or video disk recording, the output of the delay or storage device to the brightness or color system must be synchronized to the electromechanical movement of the recording medium, but the timing of this recording step may be adjusted for convenience and need not take place at the conventional speed or any fixed rate.

For purposes of the television output methods here described, the image as specified in the encounter list may be sufficient to make the desired picture, by such means as that associated with the automatic raster-checkers, above, whereby parameters predicting the encounter of an edge are used to ambush the oscillating sweep of a raster scan.

Stereoscopic photographs and movies may be produced by double performance, from two separated Ls, of the methods here called "point-by-point picture plot" and "random-plot halftone," or the line-drawing methods here described.

Two vantages, LA and LB, spatially positioned 2 or more inches apart in a human-sized scene-space, or at some other scale in scene-space of another size, are selected. Pictures are made of the same scene by any of the processes described here. The pairs of pictures may be viewed through conventional stereoscopic viewers and projection means.

A succession of thin vertical pictures from alternating vantage points, suitable for viewing behind plastic ribbed lenticular material, is produced by this method:

Four slicers are set to a set of vantages LA, LB, LC and LD, in vertical mode with p vertical and q horizontal, situated spatially in an arc around the scene, the center of the arc being at the furthest point in the scene. Excursions slice the scene vertically, with or without shadows and reflections.

Hit-points xyz go to the color-system for color lookup. The color-points are then transmitted to an output device which transcribes them in alternation.

The output picture-slices may consist each either of a column of single picture-points, or an area over which color has been plotted according to the methods described, whose borders have been determined by the slicers.

The system may also be used to create holograms. For this it employs a steered-raster technique, where the steering raster in dimensions pqLN is a pattern of concentric circles, a virtual 3-space arrangement of nested cones, or a similar structure, and steers excursions upon the represented objects according to these patterns. Rather than outputting points according to a stream or succession of surface-point coloration values, a wavefront reconstruction is simulated by the continuous or repeated measurement during the excursion of the distance from xyz to LN. When the distance is equal to an integral number of wavelengths of the radiation whose hologram is being simulated, output coloration is lightest, when it is out of phase the point is darkened, or vice versa.

An amusing extension of the ideas and approach discussed in this document will permit the realistic photograph-like depiction of trees, forests and other vegetation. In addition to the equipment and processes heretofore disclosed for the purpose of depicting curved objects, and scenes embracing them and their shadows, further equipment and processes need here to be mentioned for depicting in photograph-like ways such complex and pseudo-random phenomena as hair, leaves, etc.

This application uses an electronic hardware device which we may call the "leaf machine" (not shown). The device consists of a system of holding devices, registers or means presenting the shape of a leaf (of any variety) to a signal representing the angle and position of an oncoming search ray. The leaf machine correlates the search ray signal with the leaf profile and emits a signal revealing whether the ray having that attack hits the leaf profile, and if so, where on the leaf.

A means for "positioning" leaves in the scene by a controllable pseudo-random process is employed, for instance to depict ivy on a wall. A wall may be "covered" with a random-looking array of ivy leaves by means of a process which selects positions and angles upon the wall.

A section of such an ivied wall might be specified by the following array of entries:

1.27, 3.2, 0°	1.3, 5.1, 27°	1.2, 7.32, -6°
2.4, 3.1, 4°	1.9, 5.03, 14°	2.32, 7.4, 16°
3.6, 3.21, 13°	3.6, 5.17, 2°	3.2, 7.28, 30°

where the connecting point of the stem at the wall is specified by the first two numbers (taken as measurements on the wall), with the angle then specifying the leaf's angle of extension from that point.

Such a leaf machine and scene specification may be embraced within the equipment and processes heretofore described. We will consider the process of making a preset-array halftone picture by this method.

A search ray is directed toward the wall. Its hit-point on the wall is determined and compared with the leaf positions and angles. For every leaf near the hit-point, the leaf machine is loaded with the leaf's specifying parameters and the search ray signal presented thereto. The leaf machine then signals whether the ray hits its image of a leaf as there positioned. If so, the ray's output point is assigned a "green" color-value in the output picture; otherwise the search continues to the wall.

Shadow processes may be used in the normal manner: a ray is extended from the hit-point to any sources of light in the scene-space, and the resulting output point lightened (or darkened) in relation to the sources of light reached (or not reached); where mantle or other hereindescribed methods are used for shadowing, the method is correspondingly elaborated.

If a leaf machine is employed which holds data representing 3-D curvature of the leaf as well, specular reflectivity (as from shining ivy leaves) may be embraced within the picture. The hit-point is taken as starting-point for a new search ray, and the reflection-angle from the search ray at the hit-point as the angle for a reflection search ray.

Certain peculiarities of the pseudo-random process will be noted. One is that searches and explorations may be carried on to an indefinitely fine degree, depending on the degree of detail required. Another is that its separate ramifications in distinct parts of the scene may be explored separately, without calculations affecting the whole unit or structure. Its parts are thus independently extensible in their degree of detail.

The overall approach may be itself greatly extended. It may be used alike for certain trivial applications, such as creating mottled textures on pictures of concrete or carpets, or extended to the wholly non-trivial cases of flowing hair, forests, and the realistic animation of hair and forests (as by wind).

We are expounding the use of irregular but controllable pseudo-random systems having at least two parts, a process (for generating individual specifications in the system to a desired level of detail) and a starting setup, being a set of values, etc. to which the process is initially applied. In animation we need in addition what we may call a perturbation process. We will consider these as employed in the depiction and animation of a single tree. (We will deal with positioning of branches and leaves only, the trunk being an obvious extension.)

A "spindle," or vertical pole, is specified as extending upward from the chosen position on the ground in 3-space. A certain line away from that spindle is selected as its starting angle for calculations.

Possible branches of the tree are then assigned positions up from the ground, (say in a helical rotation upward of 1 foot (scene-measure) per 90° angle of rotation), spaced every 32° with

a probability of 0.27. The length of each branch, and its potential forks, are alike to be determined by similarly preset values of length, angle and probability.

The probability-decisions in each case are determined, however, by what we may call a directly determinable vari-approachable forking pseudo-random function (or process). In such a function or process, the exact determination-value for a given question is given by a calculation which can be supplied with a place or region in the scene (such as a pair of coordinates, or a plane, exemplified by an ivy-leaf position on a wall or a given height in the foliage of a tree), a degree of detail required, and a set of determiners, or initial independent variables for the function or process. "Directly determinable" means that an outcome may be readily determined without a long series of calculations from an initial state (such as we usually require to compute a factorial number or Fibonacci number). "Vari-approachable" means that irrespective of the origin of search, level of detail or point in question, the vari-approachable function yields the same determinate answer. "Forking" means that the function or process forks to yield as much detail as desired for a given query, continuing to vary its output from the same initial states as detail and length of that output increases, maintaining a suitable appearance of irregularity in such detail, and permitting examination of parts in varying degrees of detail; differing subsegments may when magnified appear to continue to differ.

In the case of the tree, let us consider a directly determinable vari-accessible pseudo-random forking process or function for tree-forks and for leaves.

First process or function: take height of tree at branch-option under study, plus reference-angle at branch-option. Add said

height to said reference-angle, each figure to be carried to as many significant places as required for the determination.

Second process or function: multiply said reference-angle by said height, each input number to be carried to as many significant figures as required for the determination.

First process determines tree forks as follows (digit if odd means "fork," if even, "no fork"):

Digit position	Determination
5	Branch from trunk or none
6	On such a branch, first fork option
7	If 6, second fork option left
8	If 6, second fork option right
9	If not 6, second option for first fork
10	If 7, third fork option left-left
11	If 7, third fork option left-right
	etc.

The second process would similarly specify the presence or absence of leaves at plausibly determined nodes along the branches so specified.

A perturbation process, such as that required to plausibly animate such a tree, as by wind, would also have to operate for individual search-cases by local calculation, possibly as some function of the above combined with wind angle, velocity and/or duration.

A desirable feature of such an animating perturbation process is that it be calculable locally to the query with minimum memory and as few steps as possible, and that it plausibly simulate the motion intended in variations over time. Thus the independent components of motion (such as, in the tree-blowing case, swing of branches and individual flutter of leaves) shall be grossly proportional to the desired overall movement and minutely proportional to the submovements needed for verisimilitude. Thus the perturbation process might have its components of randomness dependent upon features of the structure whose minute variations may be set in linear or cyclical correspondence to elapsed time within the animation.

The halftone processes that have been here described, and others (including the television methods) may be augmented by the addition of detailed shadow and specular reflectivity to any desired degree of nicety. Given the hit-point xyz and the lookup of its color rgb (ordinarily by means of flat-coordinates Auvd), a ray is extended from the hit-point to each source of light in the scene-space, and its intersection with any intervening objects in the scene-space noted. For each light reached, the output point is lightened in relation to that light's brightness (according to an additive or multiplicative process, a matter of taste); or for each light encountered the point may be proportionally darkened. This takes care of shadow for as many light sources as desired.

Similarly for specular reflectivity. Bounce process. On surfaces to be given a patina, sheen, shine or mirror finish, hit-point xyz serves as a starting-point for a new search-ray at the reflection angle (given in the equipment system herein described by reflector RFL).

Any intersection of this reflective search ray with an object or light is noted. Depending on the sheen desired, the output-point from the hit-point is modified. If the secondary ray strikes a light, the output-point is brightened, or its surface color discarded in favor of the color of the light, depending on the degree of the shine.

If an object is struck, and some degree of sheen is desired for the first surface, the hit-point on the reflection-struck object is then itself searched for illumination by the usual method, and its own color ascertained. If it is a light-colored surface found to be in bright light, the first hit-point is

correspondingly lightened. End of bounce process.

If mirror sheen is desired, for instance on a new automobile, every hit-point becomes a starting-point for a bounce process, and every hit-point found by the bounce process has its own surface color and illumination merged with the output color determined by the initial hit-points. (For true mirror or chromium finish, surface color and illumination are ignored for reflection.)

Multiple bounce process. When reflections from a very shiny object encounter another very shiny object, that object becomes in turn a source for a bounce process, and so on. Bounce processes may be recursively employed to depict very shiny scenes, for instance rainy scenes involving shop-windows, or (to take an extreme) an automobile showroom full of mirrors, where automobiles are reflected by one another.

The technicalities which have been mentioned thus far for handling shadows and reflectivity, such as RFL and mantles, should not obscure the more general processes which they have been contrived to expedite.

The shadow process (of extending search rays toward a light) is repetitively extensible; the reflection or bounce process (of bouncing a new search ray at an angle of reflection from the hit-point) is indefinitely recursive. In what may be called a simplex 3-D halftone system, each such subsidiary search ray must be calculated independently without respect to previous findings. In the system which has been described here in more detail, these subsidiary searches are carried out by semi-autonomous means, using mantles for shadow guidance and RFL for calculation of reflection angle.

The hardware and methods remarked on here permit of many variations within the scope of this invention.

A hybrid embodiment of possible hardware has been described (combining analog and digital means of surface representation, surface shell calculation, and other operations). Implementations of all-analog hardware, all-digital hardware, software or firmware, or different separation of the functions into analog and digital means, all are possible.

Triangular surface representation means have been described, in counterdescription to the more conventional rectangular representations. Representation means embracing rectangular, hexagonal and other "wallpaper patterns" are considered to be embraced within this disclosure.

The surface representation means here described generate surface shells merely from the locations of the corner points of their constituent facets, bypassing the more conventional formulaic representation of curvatures. Surface sections represented by such formulaic means, including "Coons patches," are here considered to be included within the scope of possible embodiments of the inventive concepts herein disclosed.

The mathematical formulas used here for surface curvature and projection were found convenient for the purposes of disclosure, but plainly are merely instances of such procedures selected from among many. The particular operations selected for the purpose, together with the division of machinery into functioning subunits assigned to parts of such procedure, are arbitrary, and other divisions of function within differently arranged machinery and/or programmed computer operations likewise remain within the scope

of these inventive concepts and their possible implementations.

The division of equipment and functions described here have for the purposes of elucidation included view calculating means distinct from the array, but the mathematical formulas here presented for the array embrace the view calculating function as well. Both such approaches fall within the scope of this disclosure.

The equipment here described in detail permits the simultaneous but different searching of virtual objects stored in contiguous parts of a hardware array by subdividing such an array by electronic "partitions" into separate "chambers." Other designs, also embraced within the concept of the parallel-cosearchable array, would permit some alternate means of searching such an array without the difficulties of the partition system.

For instance, one approach would employ a "bumper bit" that would maintain segregation between two excursions or excursion windows simultaneously rambling in the same array.

Another method would employ a set of alternative search controllers (similar to alternate Braiders in the implementation here described). The signals from several search controllers would be co-presented to the common array, and the subarrays to respond to specific controllers selected by some means. For instance, a selection code in each cell could be commonly set in all cells to respond to the same controller. Such a code could propagate throughout the cells of an array (like the IAS shift command heretofore described). One practical means of controlling such a general propagation of the controller-select code would have it stop when an unfilled cell is reached. This would permit

webs of data to be packed into an array without regard to "partitions" or the boundaries of "chambers." (When two probes are simultaneously directed to different parts of the same representation of an object, this could be recognized in the automatic propagation, and generate a "conflict bit," in whose presence cells near one probe would physically be restricted in responding to the other, or some such-like scheme.)

Another approach would co-present separate control signals to subsections of the array, whose subsection boundaries were shifted intermittently under the attention of the main computer.

This would suggest a method for circumventing the ungainly IAS subsystem, by which an array's response to an excursion probe is restricted to only a subset of the array. An alternative means might be contrived for restricting under external control (either by the computer or a special controller) the subarray to which the probe is presented, or to select from many simultaneous outputs of the array (by similar external means) that which is actually being searched by the probe.

Another primitive operation on the system, heretofore omitted, is what may be called "edge guarding." In the operation of edge guarding, an edgetracer is assigned to guard a particular edge during the passage of a picture-scan or some other probe. If such a probe approaches, the edgetracer is driven toward that probe in an attempt at interception. Should the probe cross the pq of the edgetracer, or pass close to it and continue at its prior heading, this is recognized as a crossing of the border (incursion or escape) and a signal to such effect is broadcast.

Another means of surface representation and generation so far omitted from the disclosure is the creation of a several-celled apparatus, similar to hex and tricell, holding simultaneously some fairly small number of surface sections (perhaps less than a hundred), having a direct replenishment source in some form of digital memory, such as core, disk or semiconductor storage. As an excursionary probe approaches an edge, automatic indexing methods could be used to extract from computer memory surface information to supply the surface segments about to be entered by the probe; cells to hold such information could be supplied out of some common pool and electrically reconnected in the proper place, could wrap around in a toroidal (double-cylindrical) connective organization, or could be freed by the shifting of the information across the array of cells.

In the case of the toroidally-organized assemblage, let us consider for example an 8x8 array of rectangular cells. The interconnectivity would be that of a checkerboard connected to itself left-to-right and top-to-bottom. Surface representation would always be in a contiguous area of 8x8, or less (to as few, say, as 6x6 cells), but with moving terminators in the horizontal and vertical dimensions indicating the borders of activity. A probe would move within this zone; a border being approached would be moved, and the contents of the cells thus opened re-filled out of the exterior memory with the required information for continued surface movement.

The TVRC may be employed to make a halftone picture showing sinuous curves of any complexity, unrelated to the scene machine. In such case the curves may be coded into a particular form, appropriate to the general type of output means; such coding of course may be carried out by automatic means upon human input. The coding may take place as follows: a) finding of extremities of curved line segments to be input, such extremities including unconnected endpoints, highest and lowest points in desired view coordinates, and forks; b) recording such topological information, together with c) difference information specifying to any desired degree of nicety the intended curvature, as first differences, second differences, etc., of the classical sort, together with d) altitude and logic information specifying separate difference domains for the difference expressions, and e) color information denoting the fields thus separated. From this condensed information the curve may be reconstructed, in real time if desired (especially with the aid of a fast TVRC) to present half-tone pictures on a television-like scan. The altitudes and horizontal positions of the aforementioned extremities provide cueing-points at which to gate the scan; the difference information provides increments, increments of increments, and increments of increments of increments, and so on if needed, to add or subtract recursively within specific distance domains to furnish cueing-points for later gatings of the same line. Gatings naturally may be line-defining pulses or area-defining color changes.

An advantage of this method is that it may be easily combined into an automatic Disney-type animation system, with the extremities being moved, and the difference expressions changed, automatically on a time-cueing basis.

The difference expressions may be derived automatically from light-pen or tablet input, and the whole scheme-- including individual pictures and their timing-- revised in part or whole by the artist without serious difficulty of programming.

Finally, sufficiently fast implementation of a direct hardware TVRC, or its equivalent in a microprogrammed computer such as the Meta 4, would permit readout into a TV system of an entire prestored enactment or photoplay from the computer system, with no need of intermediate film or videotape, into a television broadcast or closed-circuit system. Slow-time recording to some slowed-down video recording means, to be later replayed at normal speed, would also be feasible.

Certain methods will aid in the use of some of these systems in real time.

When it is desired to employ these methods of scenic depiction in conjunction with live television in real time, for instance to create apparent backgrounds, scenery or characters who are to be superimposed or included with real characters and objects, use of matte techniques ("Chroma-key") are obviously called for. This is true in either the three-dimensional or the two-dimensional approaches here described.

Integration of the system's output in three dimensions with television requires special attention (even when the third dimension may be crude animation, as with the pure TVRC system).

When a camera changes position in the real part of the scene, whether by panning, dollying, trucking or boom movement, it is desirable to change the view of the depicted object being included with that real one seen by the camera. In this case some means of feedback disclosing camera position to the pictorial computing system is necessary. These might include, for instance, data from shaft encoders, doppler radio or ultrasound systems, or other technique for informing the pictorial computing system of a change in viewing position or angle. Appropriate positional computing means would then compute the revised position of the camera lens. (Length of the focussed lens, and its position relative to the virtual film plane, would also have to be taken into account.)

A similar procedure, though not working in real time, could be used for initial shooting of motion pictures to which artificial depictions are to be added. In such a case the feedback specifying camera motion would be recorded by some synchronizing means; for

instance, tracks of multitrack sprocket-synchronized audio tape used for motion picture sound recording could be devoted to such camera-motion recording, and such tracks furnished the computing system. This would permit the exact synchronization of changes in view or animation with the part of the motion picture to which it is desired that they be matted-in.

Where the human touch in animation is desired, input to the pictorial computer system could be by conventional puppeteering means or some variant: crossed sticks with hanging strings leading into a well wherein the strings are attached to spring-loaded sensors, for instance; these sensors would be taken as inputs to a program displaying figures, and perhaps their expressions and the movements of their mouths, on a display screen at the same time. The user, acting now as puppeteer, would have a direct sense of the consequences of his motions. The sensor inputs and their timing could be recorded, permitting later reenactment, the detailing or modification of such enactment in subsequent animation editorial processes. (In real-time output they could control real-time action

Another equivalent input would be a hand-socket like that within the head and arms of a hand-puppet, having in addition perhaps controls such as loops or levers for manipulation of eyes, mouth or other features. Or an actual wooden or rubbered-over face with concealed sensors, together with movable features-- articulated with springs for the wooden, possibly cable-tendons for the rubberized-- would permit the animator to work successive positions and expressions, these being transferred to a recorded enactment.

In the editorial process for such recorded enactment, other tools-- especially the computer input tablet, such as the digitally encoding "Rand" tablet-- could be used to provide tempo of movement in the retiming of the enactment.

The above disclosure has been given by way of illustration and elucidation, and not by way of limitation, and it is desired to protect all embodiments of the herein disclosed inventive concept within the scope of the appended claims.

Claims

What is claimed is:

1. A spatial presentation system, comprising: holding means holding space intelligence respecting the shape of a surface spatially disposed in a three-dimensional scene; surface generation means combined with said holding means and receiving signals of said space intelligence from said holding means; calculating means forming part of said surface generation means calculating surface intelligence, respective of surface points, consisting of characteristics of specific points on the surface and their positions relative to contents of said scene.

2. A graphical presentation system, consisting of a spatial presentation system as in claim 1, having view calculator means combined with said surface generation means, said view calculator means calculating from said surface intelligence the projected pictorial positions of said surface points, representing the positions of corresponding points on a planar picture corresponding to a specifiable projected prospect of said scene.

3. A graphical presentation system, as in claim 1, comprising: excursion controller means attached to said surface generation means, said excursion controller means emitting a guiding signal to said surface generation means, said guiding signal consisting of variations within a control domain corresponding to said surface; said guiding signal stimulating said surface generation means to emission of said surface intelligence.

4. A spatial representation array system, comprising: array holding means holding space intelligence, respecting the shape and spatial position of a surface spatially disposed in a three-dimensional scene; representation cells composing said array holding means, said representation cells being similar and distinct units holding surface intelligence, which individually present distinct assemblages of said space intelligence respecting differing aspects of a represented surface.

5. Array holding means, as in claim 4, having representation cells individually presenting part information respecting different areas of a surface.

6. Array holding means as in claim 4, having data registers whose contents may be shifted between representation cells, from cell to cell in a common direction, forming thereby a shift register shifting in that direction; specific parts of the information so shifted lodging as a result in corresponding parts of the contiguous representation cells to which they are shifted.

7. Wallpaper array holding means, comprising array holding means, as in claim 4, wherein said assemblages of part-information stored in said representation cells represent adjacent surface sections topologically resembling in their edge-connections part of a mathematical wallpaper pattern.

8. Wallpaper array holding means, as in claim 7, where the wallpaper pattern consists of triangles.

9. Wallpaper array holding means, as in claim 7, where the wallpaper pattern consists of rectangles.

10. Array holding means as in claim 4; surface generation means combined with said array holding means, receiving therefrom manifestations of said space intelligence from said holding means; said surface generation means calculating surface intelligence, respective of surface points, said surface generation means so providing its computations as to produce surface intelligence having smoothly consistent signal characteristics while making transit among contributing representation cells.

11. Means as in claim 4; surface generation means combined with said array holding means, being divided into surface generation cells; said surface generation means receiving from said array holding means manifestations of space intelligence; said surface generation means calculating surface intelligence, respective of surface points; said surface generation cells individually performing surface generation calculations respective to individual parts of surface.

12. Means as in claim 11, wherein certain elements of space intelligence are shared between surface generation cells, such sharing consisting of presentation of said elements of space intelligence to more than one individual surface generation cell.

13. Means as in claim 10, which generates surface intelligence from information including representations of surface points, and curvatures interpolated theramong.

14. Means as in claim 13, which generates surface intelligence on the basis of information respecting the corner-points of contiguous surface sections.

15. Means as in claim 10, view calculator means combined with said surface generation means, calculating from surface intelligence projected positions of surface points with respect to a given prospect, maintaining in signals indicative of said projected positions with respect to said given prospect consistent signal characteristics while transit occurs between contributing cells.

16. Means as in claim 15, permitting variation by fine increments of input domain and outputting surface points exhibiting corresponding variation by fine increments.

17. Means as in claim 10, excursion controller means attached to said means, said excursion controller means emitting guiding signal to said surface generation means, said guiding signal consisting of variations within a control domain corresponding to said surface; said guiding signal stimulating said surface generation means to emission of said surface intelligence.

18. Means as in claim 17, maintaining consistent signal characteristics during transit across contiguous sections of surface, corresponding to transit of guiding signal among control domains sectors corresponding to said contiguous sections of surface.

19. Means as in claim 17, controlled with a guiding signal directed indifferently to a collection of cells, said guiding signal eliciting appropriate response from cell holding surface intelligence corresponding to input domain sector, and calculating said surface intelligence corresponding to said guiding signal.

20. Means as in claim 10, providing appropriate response to guiding signal from among collection of cells during transit of said guiding signal among separate control domain sectors corresponding to surface sections represented by said cells, by signal supersession means, said signal supersession means enabling output of appropriate units and disabling output of inappropriate units as control signal crosses boundaries of corresponding control domain sectors.

21. Means as in claim 18, providing appropriate response to guiding signal from among collection of cells during transit of said guiding signal among separate control domain sectors corresponding to surface sections represented by said cells, by an encoding excursion controller means, said encoding excursion controller means emitting an encoded guiding signal to said means, said signal containing variations in a control domain and a combination-lock code, said combination-lock code affecting decoding logic within constituent parts of the cell, the relation of said combination-lock code to said decoding logic changing with the crossing of said signal across boundaries of control domain sectors, said logic permitting the part to function or prohibiting it from functioning, depending on whether the instantaneous code in the driving signal is compatible with the code stored in said decoding logic.

22. Means as in claim 21, having associated with an individual cell a changeable register storing changeable individual code in said decoding logic.

23. System employing means as in claim 7, compensating for topological mesh irregularity, said system comprising: said wallpaper array holding means, compensating for irregularities in space intelligence, said irregularities comprising nonconformity of space intelligence data structure to said wallpaper patterns; such compensation consisting of: association with the space intelligence of information specifying the particular irregularities; the switching of effective cell responsivity to different cells from those which would be normally affected when guiding signals reach irregular portion of space intelligence.

24. Mesh irregularity compensation system, as in claim 23, where said switching of responsivity to different cells takes place by adjusting said guiding signals to compensate for the irregularity.

25. Mesh irregularity compensation system, as in claim 24, where said adjustment of guiding signals consists of altering the combination-lock code associated with said guiding sig to jump the guiding signal to another control domain sector.

26. Subarray holding means, comprising means as claim 4, said array being separable by signal control means to independent subarrays of cells.

27. Subarray holding means as in claim 26, one of said subarrays being combined with surface generation means calculating surface intelligence respective of surface points.

28. Means as in claim 27, the array holding means being subdivided into subarrays of representation cells by a changeable code within logic registers associated with constituent units; said changeable code specifying units whereat is to form a boundary for the passage of responsivity.

29. Means as in claim 10, said view calculator means maintaining continuous signal quality and character during transit of output between cells representing different surface segments.

30. Means as in claim 29; excursion controller attached to said means, said excursion controller emitting a guiding signal to said means, said guiding signal consisting of variations within a control domain corresponding to said surface; said guiding signal stimulating said surface generation means to emission of surface intelligence; said guiding signal transiting domain sectors corresponding to different surface sections and eliciting series of responses maintaining continuity of signal quality and character.

31. Means, as in claim 27, having surface generation means combined with two subarrays, from whose said subarrays of cells are elicited distinct surface intelligence signals by directing to said subarrays separate guiding signals.

32. Means, as in claim 31, divided into subarrays one of which figures in the control of another, said control being effected by the transmission of an output signal from one subarray to another, whereat it serves as a portion of the guiding signal affecting that other subarray.

33. Means as in claim 1; slicing means connected to said means, said slicing means comprising: evaluation circuitry for the recognition of signals having characteristics of a planar contour slice transecting a surface in three-dimensional space, combined with steering circuitry pursuing such a signal through variations indicative of further positions on that planar contour slice, by holding said signal to said slice characteristics.

34. Means as in claim 1; homing means connected to said means, said homing means comprising: evaluation circuitry for the recognition of signals having characteristics of surface-points in three-dimensional space intersected by particular straight rays penetrating through the scene, said straight rays being specified to said evaluation circuitry.

35. Means as in claim 1; edgetracer means connected to said means, said edgetracer means comprising: evaluation circuitry for the recognition of signals having characteristics of the relative edge of a view of an object in three-dimensional space, combined with steering circuitry pursuing such a signal through variations indicative of further positions on that viewed relative edge, by holding said signal to said edge characteristics.

36. Contrivance for switching brightness coloration in a scanned television-like display system, said contrivance having: color-time storage register holding information specifying crossing time of display scan sweep at which time brightness coloration is to change; evaluation circuitry connected to said color-time storage register, intercomparing the contents of said color-time storage register with a timing means; timing means furnishing time information to said evaluation circuitry, such time information indicating elapsed proportion of an output scanning sweep so far completed; color-change circuitry effecting change in output brightness as triggered by said evaluation circuitry when said time information indicates the same time specified by contents of said color-time storage register.

37. Contrivance, as in claim 36, having a difference storage register connected to said color-time storage register, said difference storage register holding a value representative of the amount and sign of the next change to occur in contents of the color-time storage register, and having a difference-time register associated with said difference storage register, said difference-time register specifying the time, as a number of line sweeps, at which said color-time storage register is to modify its contents, and having timing means attached to said difference-time register, ascertaining the number of line sweeps; the required number of line sweeps being made, the contents of the difference storage register being arithmetically combined with the contents of said color-time register.

38. Means as in claim 1; distance-driver means connected to said means, said distance-driver means comprising: evaluation circuitry for the recognition of signals having characteristics of points in space equidistant from a specified point of origin, combined with steering circuitry pursuing such a signal through variations indicative of further adjacent positions having such characteristics.

39. Means as in claim 1, attached to search means, said search means comprising: evaluation circuitry for the recognition of signals having a fixed set of characteristics indicative of traits of points on a surface in three-dimensional space, combined with steering circuitry pursuing such a signal through variations indicative of further positions on said surface having same traits.

40. Means, as in claim 39, whose holding means is divided into separate representation cells.

41. Computing mechanism having a control domain in two variables, said control domain being divided into sectors; different output functions associated with said control domain sectors; plurality of computing means within said computing mechanism corresponding to different output functions corresponding to said control domain sectors, each computing means sensitive to fluxantly variable control inputs, and responding to a preset combination of such inputs; control input device connected to said computing mechanism, having a plurality of signal strands carrying a fluxantly variable signal, whose combination of signals performs a selection function among the cells otherwise able to respond.

42. Mantle list means, said means comprising: information storage means for holding indications of projective convoluted virtual surfaces bounding a volume of occultation relative to a projective source, said means comprising: place holding information indicative of locations of positions on a surface within the same scene also upon said convoluted virtual surfaces, said positions being near an edge relative to the volume of occultation, said edge being the nearer edge to the projective source; associated with said place, a place holding information indicative of locations of positions on a surface also upon said convoluted virtual surfaces, said positions being at the farther surface from the projective source.

43. Encounter list means controlling television-like scan-type output of a picture, said means comprising: place of storage holding information specifying position of uppermost parts of lines, said uppermost part being a place in the picture where said line terminates, forks or bends back, associated with a place of storage holding information specifying curvatures of said lines in the picture, associated with a place of storage holding the information specifying positions of lowermost parts of said lines.

44. Means as in claim 26, divided into two subarrays, each combined with surface generation means, the first of said subarrays generating signal indicative of a point on a surface in a three-dimensional scene; transmission means, connected to both of said subarrays, transmitting attributes of said signal to the second of said subarrays; the second of said subarrays also generating signal indicative of a point on a surface in a three-dimensional scene, based on guidance provided by said attributes of said signal.

45. A first means as in claim 1; communication means attached to said means; a second means as in claim 1, attached to said communication means, said second means receiving signal indicative of surface intelligence calculated by said first means through said communication means; said second means being guided thereby in the series of its own surface-point calculations.

46. Means as in claim 45, said first means and said second means having holding means divided into separated representation cells.

47. Means as in claim 1; communication means connected to said surface generation means; steering means connected to said communication means and to surface generation means; said steering means outputting control signal to surface generation means; said steering means also receiving feedback information indicative of prior recent surface point signal-states and performing modifications to control signal; said modified control signal altering surface point generated by surface generation means.

48. Means, as in claim 47; said holding means being divided into separate representation cells.

49. A method, employing means as in claim 34, for ascertaining whether a straight ray through a three-dimensional space intersects with a surface in said three-dimensional space, and comprising the steps of: supplying holding means with information specifying the required surfaces; supplying homing means with information specifying the required ray; starting homing means in operation; ascertaining whether said homing means returns a signal indicative of such a hit.

50. Means, employing edgetracer means as in claim 35, for tracing further mantle of an occultation relative to a given prospect, said means comprising: said surface generation means attached to said edgetracer means outputting signal indicative of succession of points on relative edge with reference to said given prospect of surface in a three-dimensional scene; communication means attached to said edgetracer means, carrying aspect of said signal; homing means attached to said communication means and receiving said aspect of said signal; holding means and surface generation means attached to said homing means, said homing means employing said aspect of said signal as homing-ray information for calculation of surface-point intercepted by homing ray.

51. Means as in claim 50, where holding means consists of multiple representation cells.

52. Method, employing means as in claim 50, for tracing edges of relative occultation, said method comprising the steps of: tracing relative edge of occultative object with respect to particular prospect in three-dimensional scene, communicating said signal representative of edge intelligence to homing unit coupled to holding means and surface generation means holding intelligence indicative of surface further from vantage of said prospect in said three-dimensional scene, said homing means tracing further relative edge thereon.

53. A method, performed with means as in claim 35, for pursuing a search ray by an edgetracer; performed with said edgetracer means, view calculator means combined with said edgetracer means; first communication means connected to said view calculator means; comparison means connected to said first communication means; second communication means connected to said comparison means; second view calculator means connected to said second communication means; second holding means connected to said second surface generation means; said method comprising the steps of: generation by said edgetracer of first signal indicative of point having signal characteristics of point on relative edge of first surface; generation with second surface generation means of second signal indicative of point on second surface represented by information in said second holding means; transmission via said communication means of signal indicative of said point on surface; comparison by said comparison means evaluating discrepancy between view calculator signals representing view coordinates of said first signal and said second signal; modification of edgetracer control signal to bring its edge position closer to other signal.

54. A method for "edge guarding," employed upon means as in claim 53, said process comprising the steps of: setting of edgetracer on relative edge of a surface; movement of said second signal across a surface; calculation of adjustative signals lessening view-coordinate signal discrepancy between said first and said second signal; trigger of recognition signal when said view-coordinate signals are nearly equal, indicating that said second signal is passing said edge being guarded by said edgetracer

55. The method, employed upon means as in claim 53, of finding the intersection of two edges in a view of a three-dimensional scene, having in addition to said means: second edgetracer means connected to second surface generation means; said method comprising the steps of: setting both edgetracer means to the said projective origin; using said discrepancy signal to modify the behavior of both edgetracer means until their view coordinates are in approximate convergence.

56. A method, to be employed upon means as in claim 52, of creating a list specifying projected convolutions of occluded volumes, said process comprising the steps of: tracing of edge of near object by means of edgetracer; following view coordinates of surface signals output by edgetracer with homing unit relative to projective prospect; on the crossing of relative edges within the scene, recording information indicative of the projectively near and far positions of such edges in the corresponding locations of said list.

57. The method, employing edgetracer means, as in claim 35, of creating a list specifying picture elements and curves to be encountered in sweeping scans of a straight ray across a three-dimensional scene, said method comprising the steps of: tracing relative edges with respect to a given prospect on surfaces in three-dimensional scene; upon signals from said edgetracer means indicating downturns of such edges with respect to view coordinates, marking the highest points of such edges in a list storage means; upon signals from said edgetracer indicating upturns of such edges with respect to view coordinates, marking the lowest points of such edges in a list storage means; upon signal from said edgetracer

indicating terminations of such edges, marking said terminations in list storage means.

58. The method, employing means as in claim 1, of tracing a color-edge in a three-dimensional scene, said method comprising the steps of: furnishing control-domain values specifying color boundaries to said means, which values pass to surface generation means, which result passes to view calculator means, tracing desired succession of points constituting equicolor line.

59. The method, employing means as in claim 34, of ascertaining the picture-value of a specular reflection of a straight ray from a surface-point in a three-dimensional scene represented in said means, said method comprising the steps of: ascertaining the angle of reflection of the instantaneous ray to the instantaneous point it hits; providing said angle of the reflected ray to homing means; receiving from homing means the location of hit-point on other surface that reflection reaches; ascertaining color of said surface at said point.

60. Method as in claim 59, extended for reflections among multiple surfaces; consisting of recursively taking hit-point and reflection angle on successively hit surfaces, and furnishing said angle and said hit-point to be used as point of origin for next employment of homing means.

61. A method, using means as in claim 1, for output coloration of a picture-point, said method comprising the steps of: determining to be suitable the position of a point supplied by surface generation means; ascertaining the control values of the guiding signal eliciting the representation of said point; looking up, in color storage means, information indicative of colorations relevant to said control values; ascertaining the relation of said control values to said colorations; ascertaining exact color-value associated with said control values.

62. A method, employing homing means as in claim 34, of incorporating shadow in a point of a picture of a three-dimensional scene by successive modifying operations upon color-values of the output-point transmitted to said picture, said method comprising the steps of: ascertaining the spatial position of a non-occluded point on a surface in a scene; employing said homing means, taking as origin said point and performing a search toward a light source in said scene; if straight-ray path to light source is unobstructed, brightening said output point as if lit;
if said straight-ray path is obstructed, darkening point as if enshadowed.

63. A method, employing edgetracer means as in claim 35, of incorporating shadow in a point of a picture of a three-dimensional scene by use of a record associating positions on far edges of a projective mantle with positions on near edges of a projective mantle, said method comprising the steps of: ascertaining the spatial position of a non-occluded point relative to pictorial vantage on a surface in a scene; summoning such record of projectiv mantle; setting said edgetracer means to edge-tracing on edge nearer the light specified by said record of projective mantle; setting homing means to following of edgetracer means; determining whether point in question lies on illuminated or non-illuminated side of shadow mantle edge; brightening said point if illuminated, darkening it if non-illuminated.

64. A method, employing homing means as in claim 34, of incorporating specular reflection in a point in a picture by modifying operations upon color-values of output-points sent to said picture, said methods comprising the steps of: ascertaining the spatial position and angle of an original point, non-occluded relative to pictorial vantage, on a surface in a scene; ascertaining color of said original point by a lookup means; setting said homing means searching along a secondary ray emanating from said point at an angle of reflection from said point equal and opposite to the angle of approach to said point of original straight ray from the pictorial vantage; finding secondary point in scene hit by said secondary ray; ascertaining color of said secondary point by a lookup means; combining color-value of said original point with color-value of said secondary point to obtain final output coloration.

65. A method, employing means as in claim 1, of creating video recordings for playback over television systems, said method comprising the steps of: tracing upon said means the viewed positions of a non-occluded surface point; assigning color to said surface point; converting said color-value to electrical signal; sending said signal to video recording means.

66. A method, employing means as in claim 50, of making a picture by tracing lines of shadow in a three-dimensional scene by use of a record associating positions on projective edges of a projective occultation mantle with positions on receiving edges of a projective occultation mantle, said method comprising the steps of: ascertaining positions on edges of shadow far from light from said record; finding positions on edges of shadow near to light associated with said positions far from light, using said record; tracing edge near to light with edgetracer, employing said positions near light as starting positions; tracing edge far from light with homing means following said edgetracer; calculating view of resulting surface points and transmitting said view to output device.

67. A method, using encounter list means as in claim 43, of scanwise output of a curved-line picture, said method comprising the steps of: scanwise output in successive repeated sweeps from one edge of the picture area toward the second edge of said picture area; association of extremities of said curved line of said picture with stored signals indicating proportion of total number of sweeps per picture to be reached prior to the display of said extremities; comparison of said stored signals with indicator showing proportion of sweeps yet accomplished; upon matching of said stored signal with contents of said indicator, engaging of timing means timing proportionality of sweep to intercomparison with stored line position of endpoint; (A) upon matching of said stored line position with said proportionality, release of color-change information to brightness system; (B) on successive sweeps, arithmetic combination of stored line position with curvature modification quantity; repetition of steps (A) and (B) until other extremity of curved line is reached.

68. A method, using equipment as in claim 1, of making line pictures, said method comprising the steps of: tracing lines upon said surface means, the consequences whereof being translated by said view calculator means into bivariate view coordinates; said bivariate coordinates being translated to electrical signals; said electrical signals being transmitted to plotting apparatus operating from x and y coordinates.

69. A method, using means as in claim 34, for creating a halftone picture, said method comprising the steps of: defining prearranged array of positions whose variant coloration is to constitute the intended picture; employing said homing means to probe into a stored scene-space a system of straight rays, said rays having among them the angular relations such that a cross-section through the bundle of said rays constitutes an array of positions like those in said prearranged array; ascertaining the first surface-point intercepted by each ray; ascertaining the coloration of said surface-point; transmitting said coloration to the corresponding position of said picture.

70. Method as in claim 69, where the positions of said prearranged array constitute a regular array of dots.

71. Method as in claim 69, where the positions of said prearranged array constitute in themselves a pictorial pattern.

72. Method using means as in claim 1, of creating a halftone picture consisting of an irregular sprinkled scattering of picture-points, said method comprising the steps of: selecting points on surface to be shown in picture by randomizing method.

73. A method employing means as in claim 34, of creating a halftone picture, said method comprising the steps of: supplying said homing means with steering signals defining a raster across the picture-area to create desired scanning pattern; said homing means pursuing said steering coordinates and tracing out a series of positions upon surface in scene, said series of positions furnishing signals for ascertaining coloration by lookup means; said coloration signals being transmitted to output device; said output device transmitting decoded colors to output medium.

74. Method as in claim 73, where said raster is a television scanning raster.

75. A method, performed with means as in claim 1, for producing stereoscopic picture-pairs by half-tone computing processes, said method comprising: selection of two separated dual vantage points in scene, creation of half-tone pictures from said separated dual vantage points.

76. A method for producing stereoscopic pictures viewable without equipment, said method comprising the steps of: computing first slice of a view from a first vantage point; computing second slice of a view from a second vantage point; intercalating said slices in parallel alternation positioned for viewing through translucent viewing means having parallel lenticular ridges focussing different views of said slices at angular displacements differentially visible to left and right eye, effecting the illusion of a three-dimensional view of the scene.

77. A method, employing means as in claim 35, for making scanned pictures of curved surfaces, said method comprising the steps of: tracing the edges of surfaces viewed in said scene by edgetracer means; ascertaining the extremities of said edges and storing information indicative of the locations of said extremities the different extremities of a given curved line being correspondingly associated in said storing; ascertaining curvature information, specifying the curvature in said view of said curved line, and performing a difference analysis upon said curved line, ascertaining the successive differences needed to reproduce said curved line, and storing said differences in corresponding association with said extremities; sweeping a television-like output device with successive scans, continually testing whether a scan has yet encountered said curved line; outputting an appropriate signal to brightness system when such encounter occurs; arithmetically augmenting first difference with second difference, and arithmetically augmenting sweep-time checker with new time difference, after such signal.

78. Method as in claim 77, where nth difference is augmented by n+1th difference.

79. A method, using means as in claim 57, for making scanned pictures of curved lines stored in said means, said method comprising the steps of: sweeping a television-like output device with successive scans, continually testing whether a scan has yet encountered said curved line; outputting an appropriate signal to brightness system when such encounter occurs; arithmetically augmenting first difference with second difference, and arithmetically augmenting sweep-time checker with new difference, after such signal; repeating process until line is fully depicted.

80. A method, using means as in claim 35, of creating a television picture by a plurality of said means, said method comprising the steps of: employing edgetracing means to ascertain highest extremity of edges in picture; poising edgetracing means at said highest extremities; pursuing normalized downward sweep of successive scans; (A) upon passage of scan through vicinity of edgetracer means, sending appropriate brightness signal to brightness mechanism of scanning picture system; tracing by edgetracer means downward along respective edge to plane in scene projecting to altitude of next crosswise scan, prior to traversal of said scan repetition of step (A).

81. A method, using means as in claim 38, of creation of a simulated hologram upon said means, said method comprising the steps of: setting said distance driver to a fixed distance equivalent to a certain number of multiples of wavelengths of simulated coherent light; setting a virtual plane representing holographic film into said scene; fixing said driver means upon a specific point on a surface in scene, then tracing an outline on said virtual plane of all points which said distance driver can reach without occlusion; tracing output points on output device replicating said tracing of said outline.

82. Means as in claim 10, and a dividing line separating those cells representing a contiguous area, said dividing line forming a barrier to movements of a signal indicative of a point on the surface represented in said means; said dividing line being movable by rows to successive rows of cells, which having been successively moved by rows across to the physical extremity of said array, makes its next move in the same direction from the other side of the array; its dividing properties remaining constant in all positions; and the array so divided acting as a concerted whole up to that division in all of its positions.

83. Method as in claim 72; with control exercised over the quantity of output points within small areas of said picture by quantizing method restricting number of said points.

84. Means as in claim 1, said surface generation means outputting signal indicative of the immediate angular orientation of surface at point represented by said signal.

85. Means as in claim 1; randomizing means connected to said means, employed for making halftone pictures of irregularly flourishing organic excrescences.

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Exploring and photographing these imaginary scenes was the purpose of the equipment and methods described in this patent application, which distills Nelson's methods worked out in the 1960s.

Ray tracing, commonly used now, was only one of the methods.

Nelson's technique of curving over triangles has not been used by Hollywood, but appears to have been recently rediscovered. It may be just right for gaming with today's high-power graphics boards

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